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Dortmund, Germany

EES-UETP Workshop on Advanced Laboratory System Testing Methods for Modern Power Systems

Hardware-in-the-Loop (HIL) Testing of Grid-Following and Forming Inverters

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May 9, 2023

EES-UETP
Electric Energy Systems - University Enterprise Training Partnership

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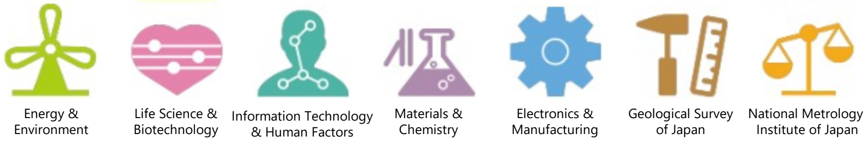
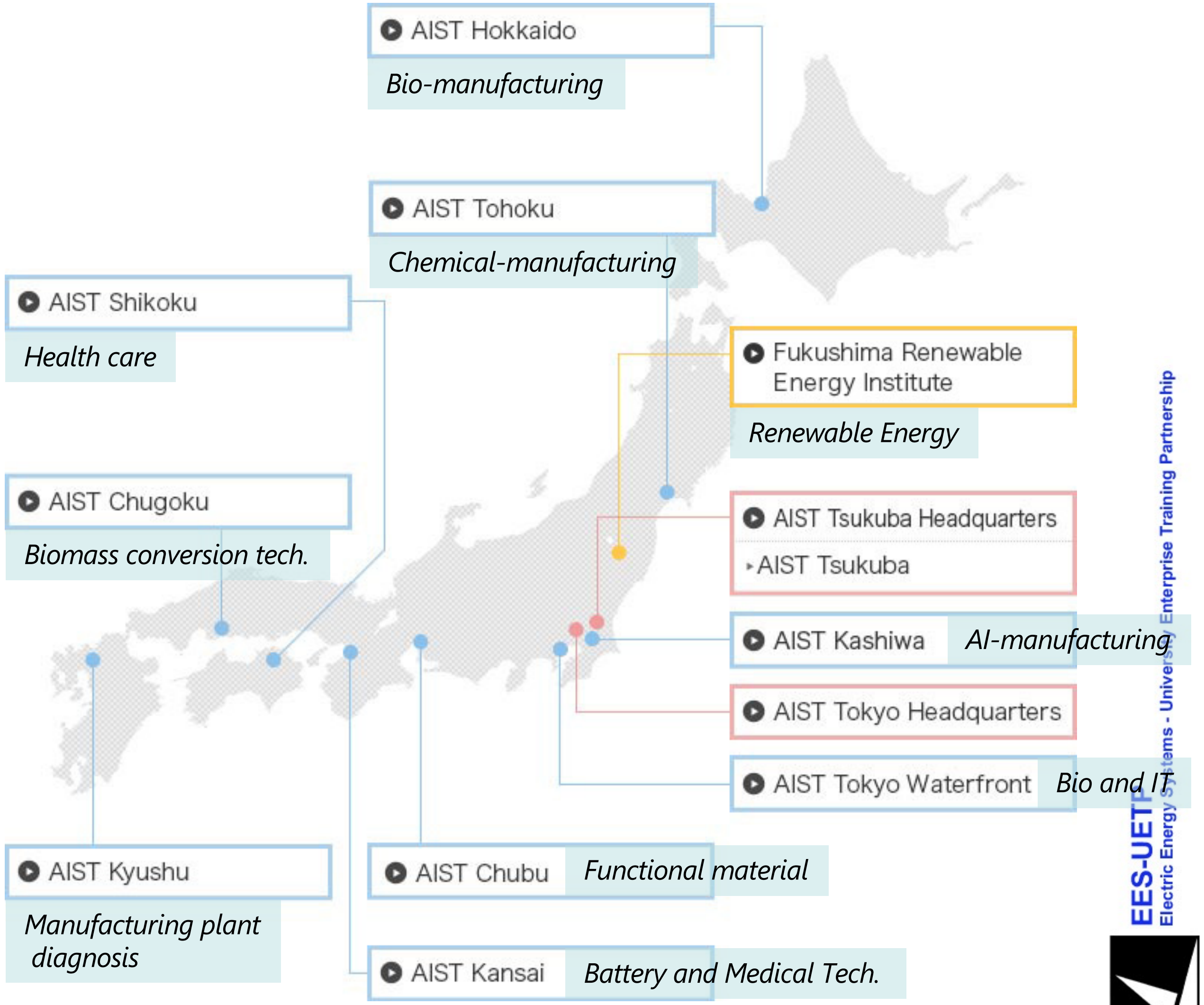
AIST (National Institute of **A**dvanced **I**ndustrial **S**cience and **T**echnology)

- Established in 2001 by reorganizing 16 institutes under METI
- Total income: 110 billion JPY
  - 90%: Government, 10%: Industry
- 2901 employees (as of July. 2022)
  - 2214 researchers
  - 687 administrative employees
  - + executives, visiting researchers, postdocs, technical staff
- 7 research departments

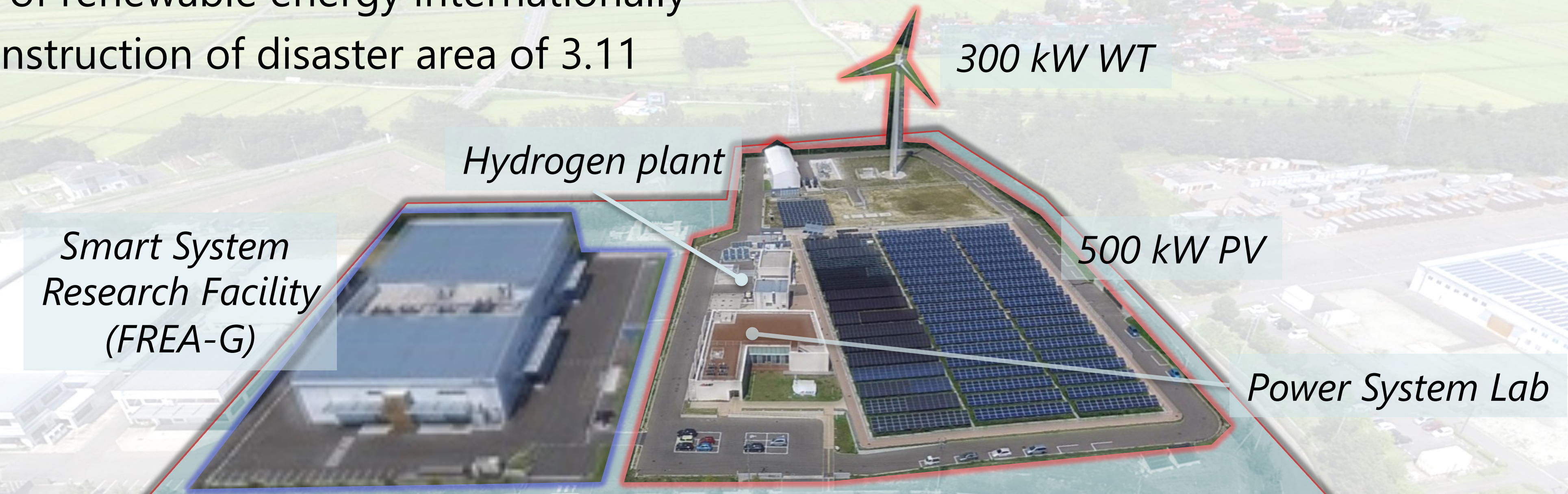




Source: AIST, JP) https://www.aist.go.jp/ , EN) https://www.aist.go.jp/index_en.html

FREA (**F**ukushima **R**enewable **E**nergy Institute, **A**IST)

- Established in Koriyama, Fukushima in 2014 for promoting
  - R&D of renewable energy internationally
  - Reconstruction of disaster area of 3.11



- Has over 200 researchers in 9 research teams

Energy Network | *Hydrogen* | *Photovoltaic* | *Wind Power* | *Geothermal* | *Shallow Geothermal*

Source: FREA https://www.aist.go.jp/fukushima/

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Power System Laboratory (Movie)

- AC source
  - Grid simulator: 500 kVA, 30 kVA
- DC source
  - PV simulator: 600 kW
  - Batter simulator: 207 kW
  - Lithium-ion battery: 16 kWh
- Inverter
  - GFM (VSG control)
  - GFL (smart inverter, virtual inertia, etc.)
- Digital real-time simulator (DRTS)
  - RTDS Technologies: NovaCor, PB5
  - Typhoon HIL: HIL604
- RLC load: 200 kVA
- Data acquisition system
- Connectivity to demonstration field

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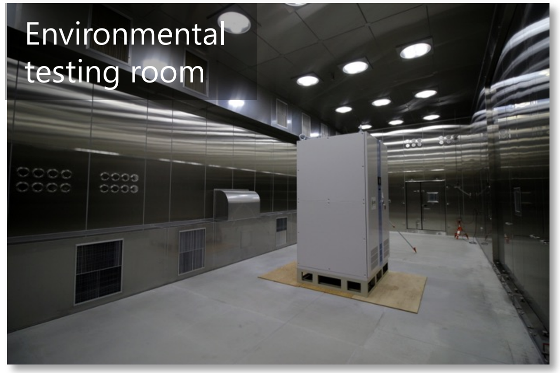
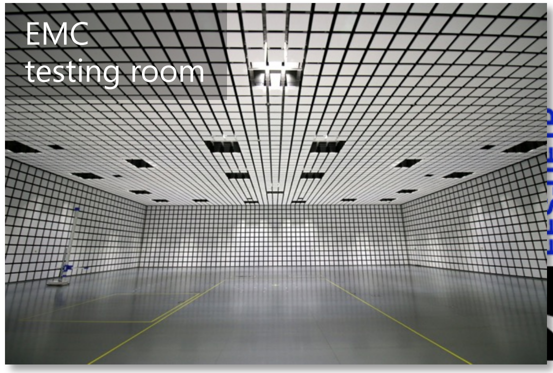
Smart System Research Facility called "FREA-G"

- Established in 2016 for testing large-size grid-connected inverters
- Testing capability
  - Grid simulator: AC 5 MVA (1.67 MVA × 3 units)
  - PV/battery simulator: DC 3.3 MVA, 2000 V
  - Grid interconnection testing room (L, M, S)
  - Environmental testing room: -40 to +85°C, 30 to 90%RH
  - EMC testing room: 34 m×34 m×7.8 m, largest in Japan





Source: https://www.aist.go.jp/fukushima/ja/outline/smart_system/index.html

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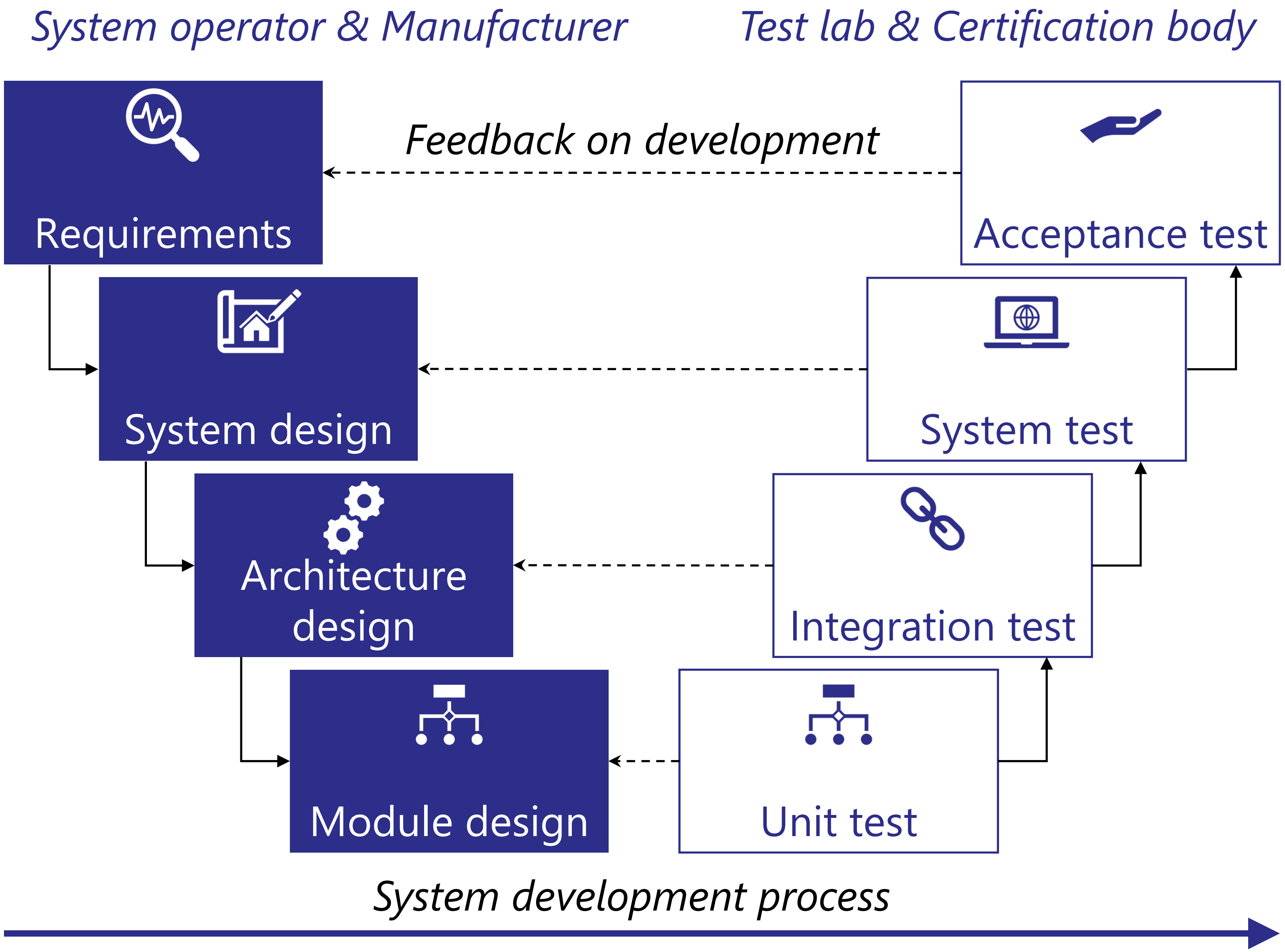
Our Team’s Role



Support R&D to accelerate distributed energy resource (DER) integration

1. Power system level
- Power system analysis
- **HIL testing**

2. DER level
- Functional development
- Conformance testing
- Standardization

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Why HIL Testing for Power Systems?

Increase in IBRs and Change in Required Roles

IBR penetration: Low → High

Evolution of grid support functions

IEEE Std 1547-2003	• **Shall NOT** actively regulate voltage • **Shall** trip on abnormal voltage/frequency
IEEE Std 1547a-2014 (Amendment 1)	• **May** actively regulate voltage • **May** ride through abnormal voltage or frequency • **May** provide frequency response
IEEE Std 1547-2018	• **Shall be capable of** actively regulating voltage • **Shall** ride through abnormal voltage/frequency • **Shall be capable of** frequency response

Source: NREL

IEEE STANDARDS ASSOCIATION

Source: C. Stice, et al., "IEEE Std 1547-2018," NERC SPIDER WG Meeting, 2019

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Significant Increase in Inverter Test Items

1547 Content Growth

	1st Edition		2nd Edition
1547 technical content:	13 pages	→	127 pages
1547.1 technical content:	54 pages	→	256 pages

New/significantly modified 1547-2018 content in red:

4. General interconnection technical specifications and requirements
- 4.2 Reference points of applicability
- 4.3 Applicable voltages
- 4.4 Measurement accuracy
- 4.5 Cease to energize performance requirement
- 4.6 Control capability requirements
- 4.7 Prioritization of DER responses
- 4.8 Isolation device
- 4.9 Inadvertent energization of the Area EPS
- 4.10 Enter service
- 4.11 Interconnect integrity
- 4.12 Integration with Area EPS grounding
- 4.13 Exemptions for Emergency Systems and Standby DER

5. Reactive power capability and voltage/power control requirements
- 5.2 Reactive power capability of the DER
- 5.3 Voltage and reactive power control
- 5.4 Voltage and active power control

6. Response to Area EPS abnormal conditions
- 6.2 Area EPS faults and open phase conditions
- 6.3 Area EPS reclosing coordination
- 6.4 Voltage
- 6.5 Frequency
- 6.6 Return to service after trip

7. Power quality
- 7.1 Limitation of dc injection
- 7.2 Limitation of voltage fluctuations induced by the DER
- 7.3 Limitation of current distortion
- 7.4 Limitation of overvoltage contribution

8. Islanding
- 8.1 Unintentional islanding
- 8.2 Intentional islanding

9. DER on distribution secondary grid/area/street (grid) networks and spot networks
- 9.1 Network protectors and automatic transfer scheme requirements
- 9.1 Distribution secondary grid networks
- 9.2 Distribution secondary spot networks

10. Interoperability, information exchange, information models, and protocols
- 10.1 Interoperability requirements
- 10.2 Monitoring, control, and information exchange requirements
- 10.3 Nameplate information
- 10.4 Configuration information
- 10.5 Monitoring information
- 10.6 Management information
- 10.7 Communication protocol requirements
- 10.8 Communication performance requirements
- 10.9 Cyber security requirements

11. Test and verification requirements
- 11.2 Definition of test and verification methods
- 11.3 Full and partial conformance testing and verification
- 11.4 Fault current characterization

NREL | 5

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Source: A. Hoke, "DER Testing and Verification - Overview of IEEE P1547.1," PJM Technical Workshop on DER Integration, 2019

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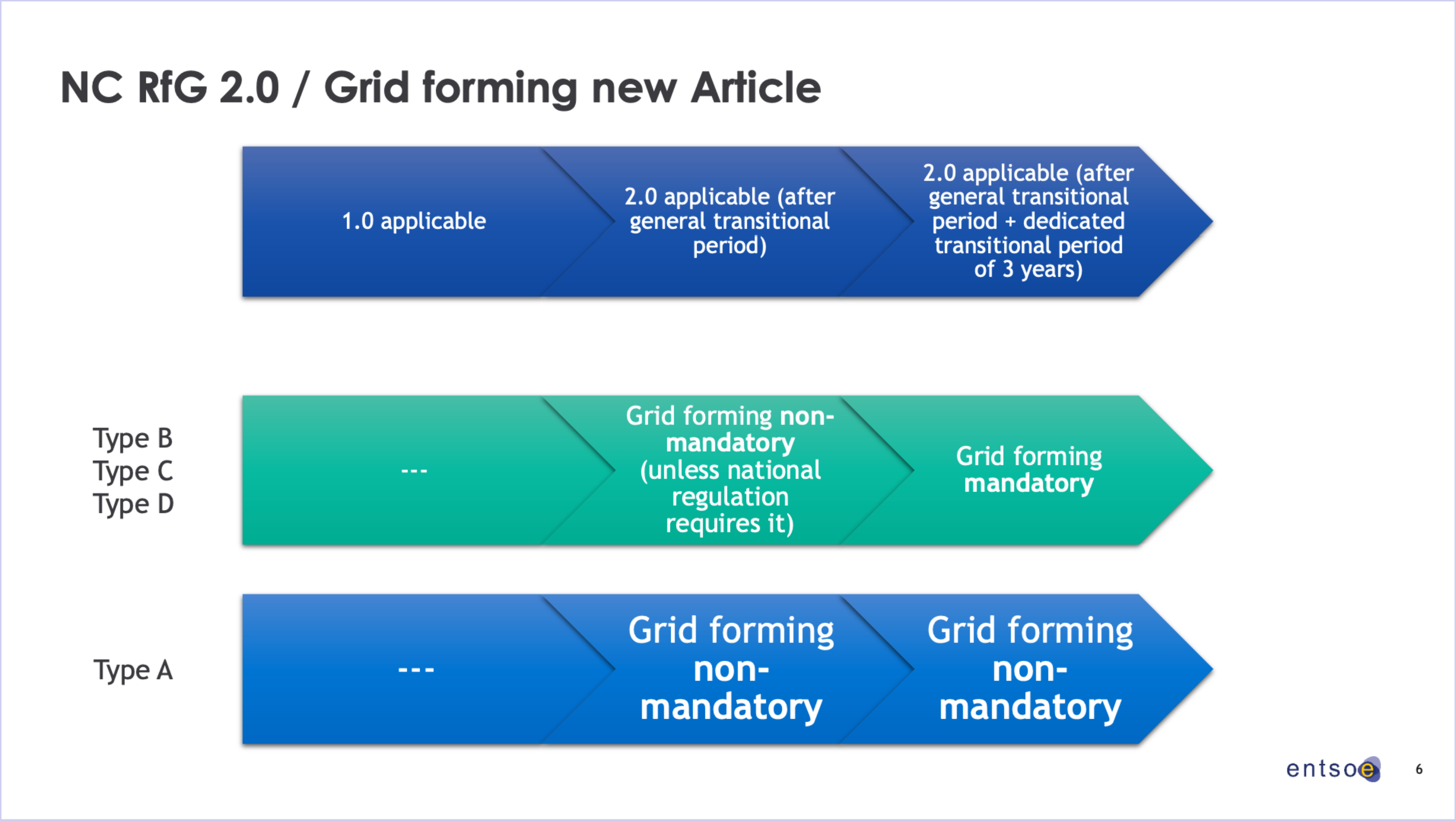
Need to Carefully Evaluate Interaction between Grid and Inverters

- Implementation of grid-forming (GFM) capability is just around the corner
  - NC RfG 2.0 with GFM requirement will be issued in 2024 and reflected in the National Grid Code in 3 years
  - Inverter performance will further impact the reliable power system operation



Source: "ENTSO-E amendment proposal for NC RfG: on Grid Forming Capability," ENTSO Public Workshop, 2022

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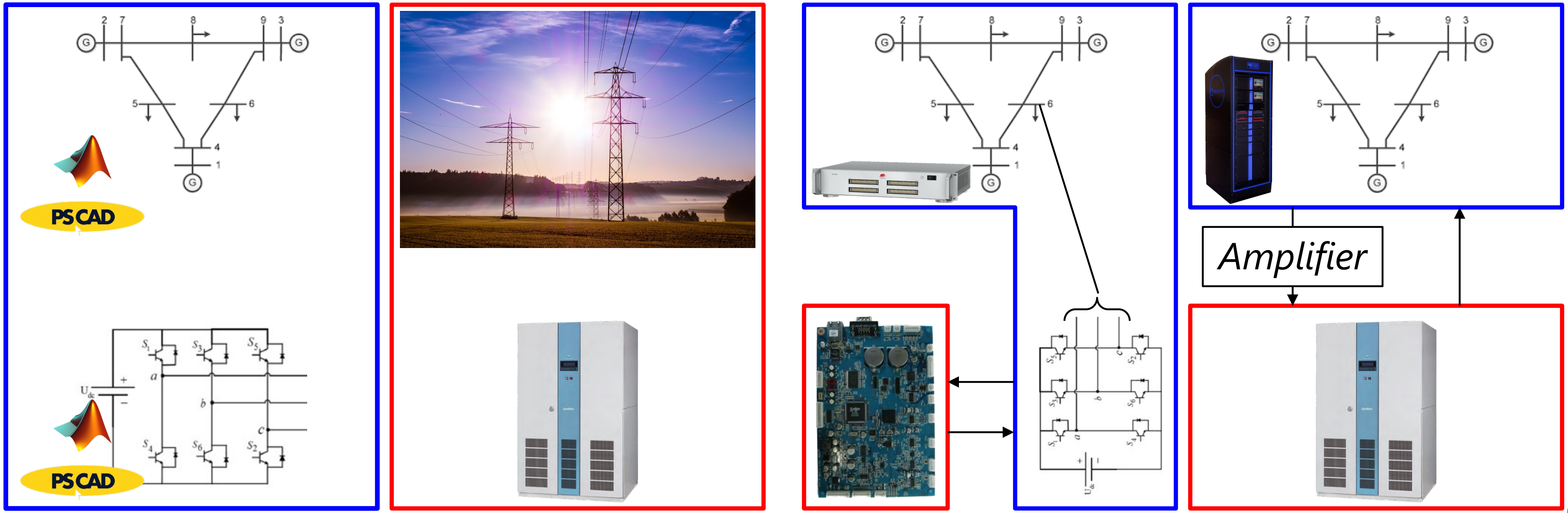
HIL Simulation is a Flexible and Reliable Testing Method

Hardware-in-the-loop (HIL) simulation

Simulation | Demonstration | **Controller HIL (CHIL)** | **Power HIL (PHIL)**

Grid

Inverter



	Simulation	Demonstration	HIL
Flexibility (Grid)	**High**	Low	**High**
Fidelity (Inverter)	Low	**High**	**High**

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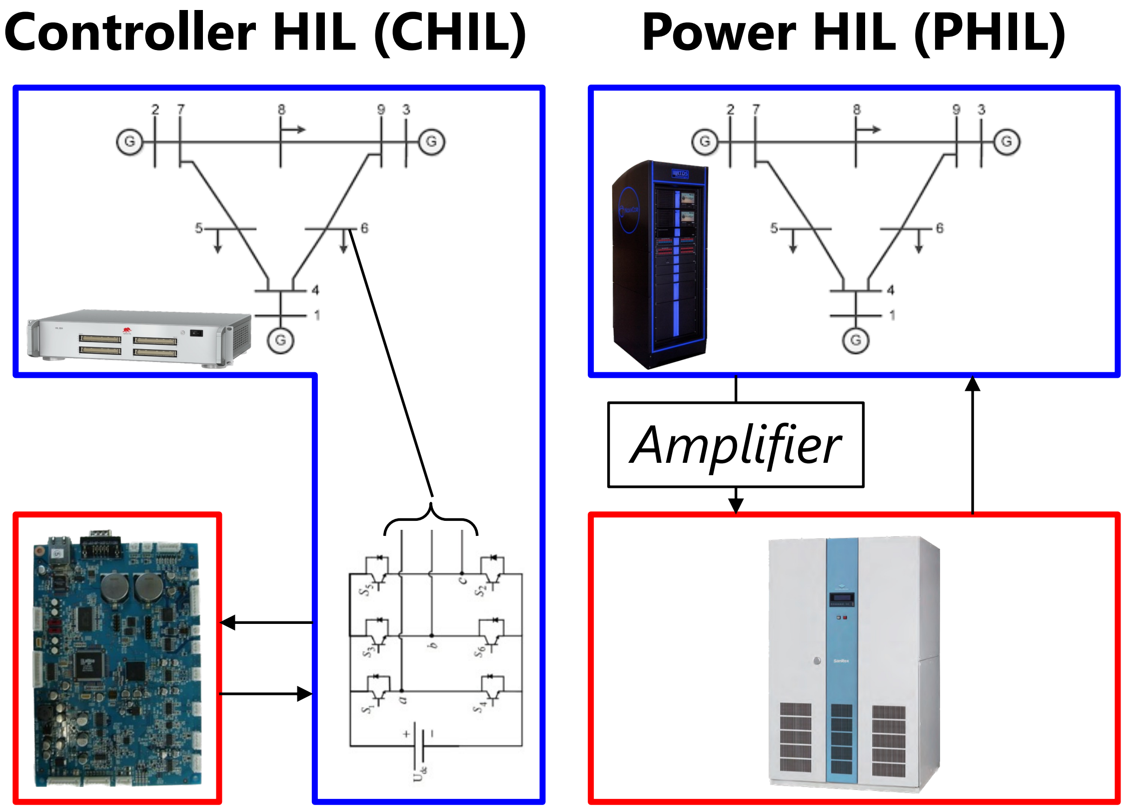
CHIL vs. PHIL

- Both are powerful verification methods, but if we had to choose…

- CHIL is simpler to implementation
  - PHIL has interface issues
  - Suitable for development by manufactures

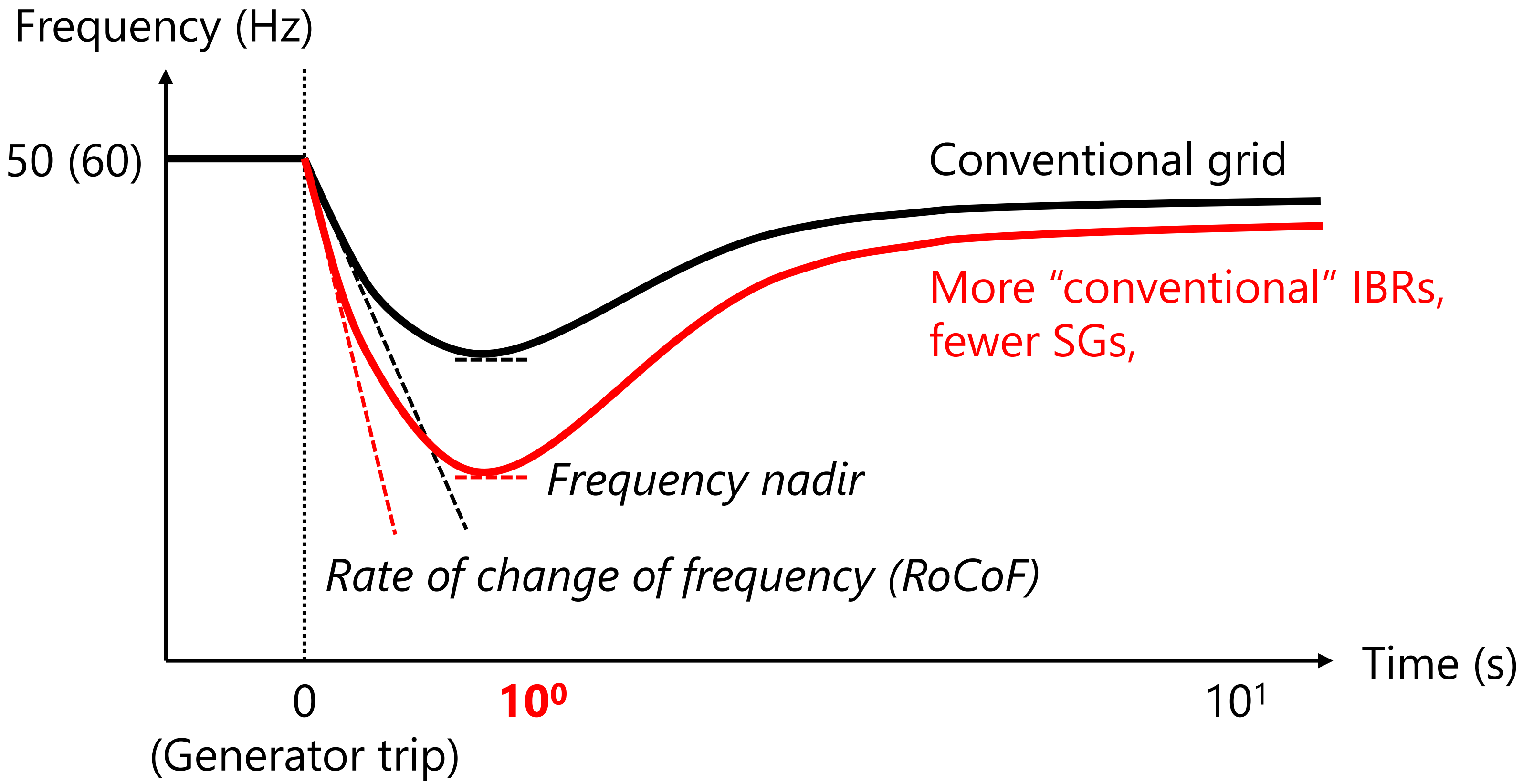
- PHIL is more realistic
  - CHIL does not include a real power unit
  - Suitable for evaluation by utility



HIL Testing for GFL and GFM Inverters with Virtual Inertia

IBR is Expected to Replace Some of Services Provided by SG

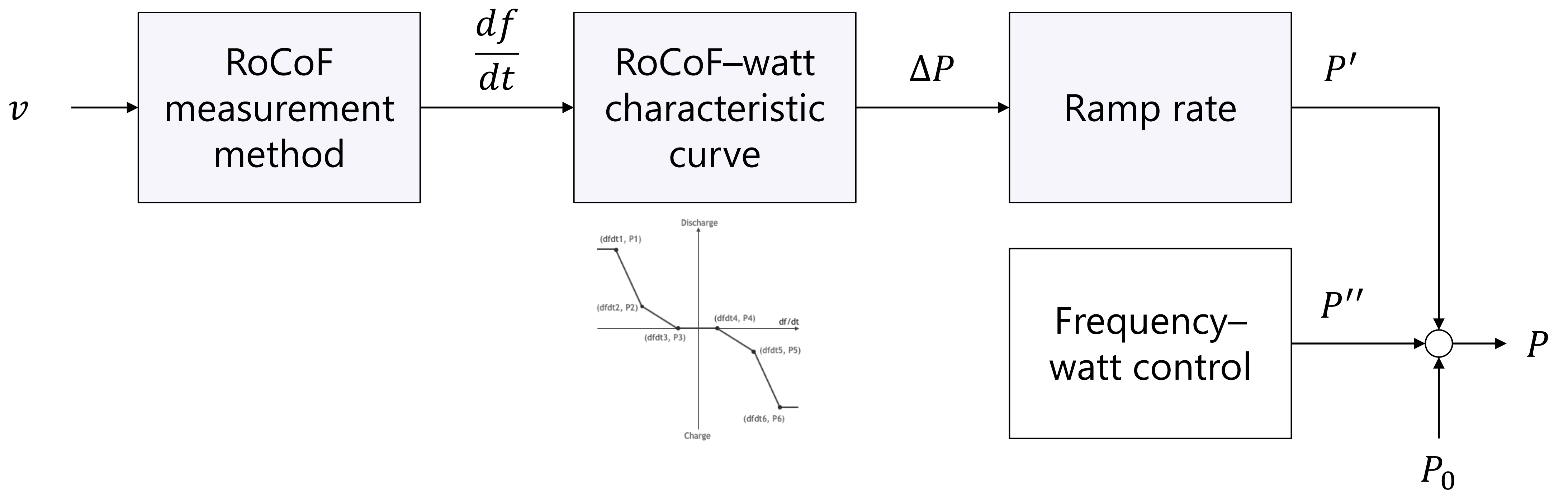
- Reducing the number of synchronous generators (SGs) decline grid frequency stability
- Frequency control including **inertial response** is required for inverter based-resources (IBRs)
- Their performance in hardware has not been discussed well



CHIL Testing to Develop df/dt Function

Development of df/dt Function

- A virtual inertia control of grid-following (GFL) inverter
  - Many control parameters
  - Coexist with other grid-supporting functions (frequency-watt, reactive power control, etc.)



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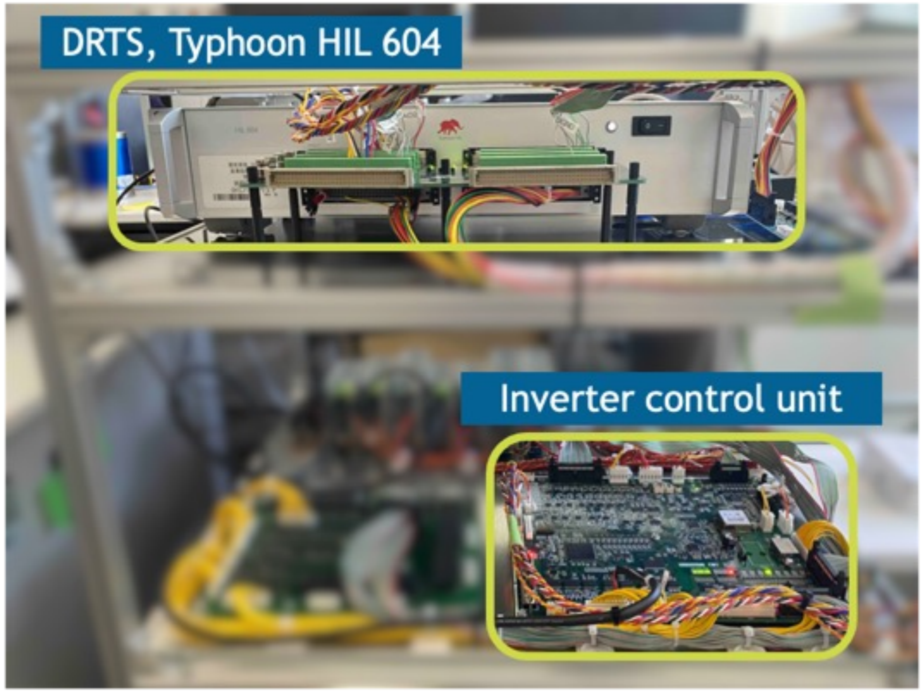
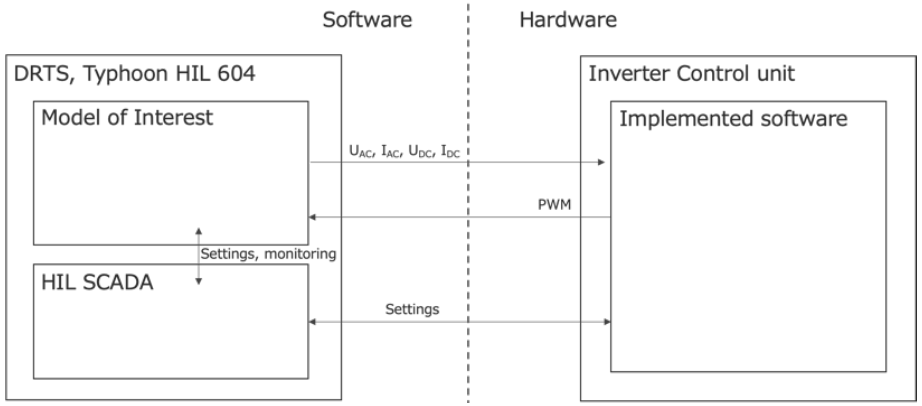
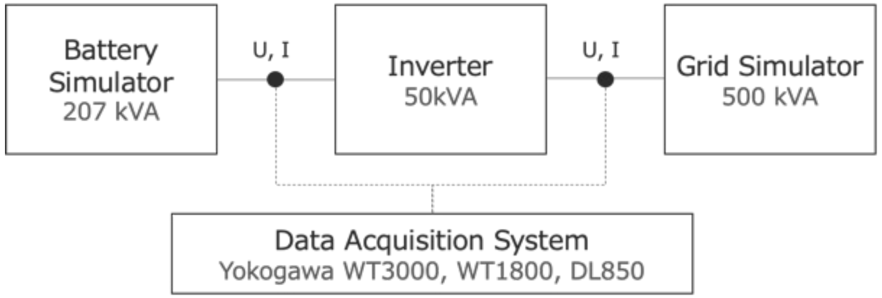
CHIL Test Accuracy Verification





CHIL setup

Inside the panel

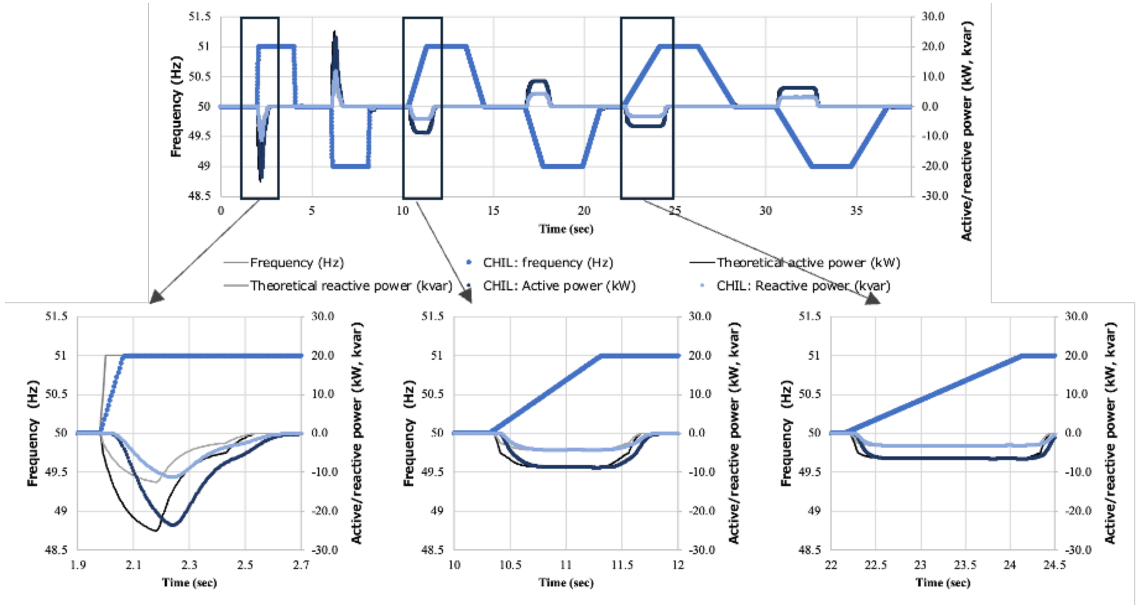


Laboratory setup

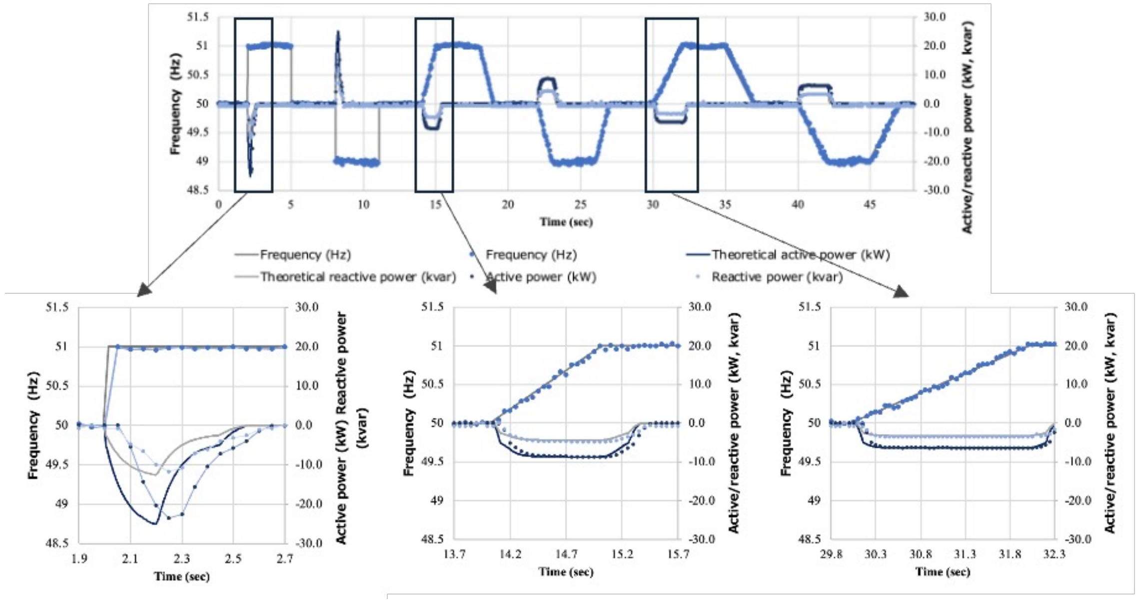
Source: J. Hashimoto, et al., "Developing a Synthetic Inertia Function for Smart Inverters and Studying its interaction with other functions with CHIL testing," Energy Reports 2023, 9 (supplement 1), 435–443.

Active/Reactive Power Response Matched within ±1.0%

Target	Num. of cases	setting	Unit
Active power setting	5 cases	-1.0, -0.5, **0.0**, 0.5, 1.0	Pu
Ramp time of frequency disturbances	3 cases	**0.0 (Step), 1.0, 2.0**	sec
Deviation of frequency disturbances	3 cases	0.1, 0.5, **1.0**	Hz



CHIL testing (controller response)



Laboratory testing (entire inverter response)

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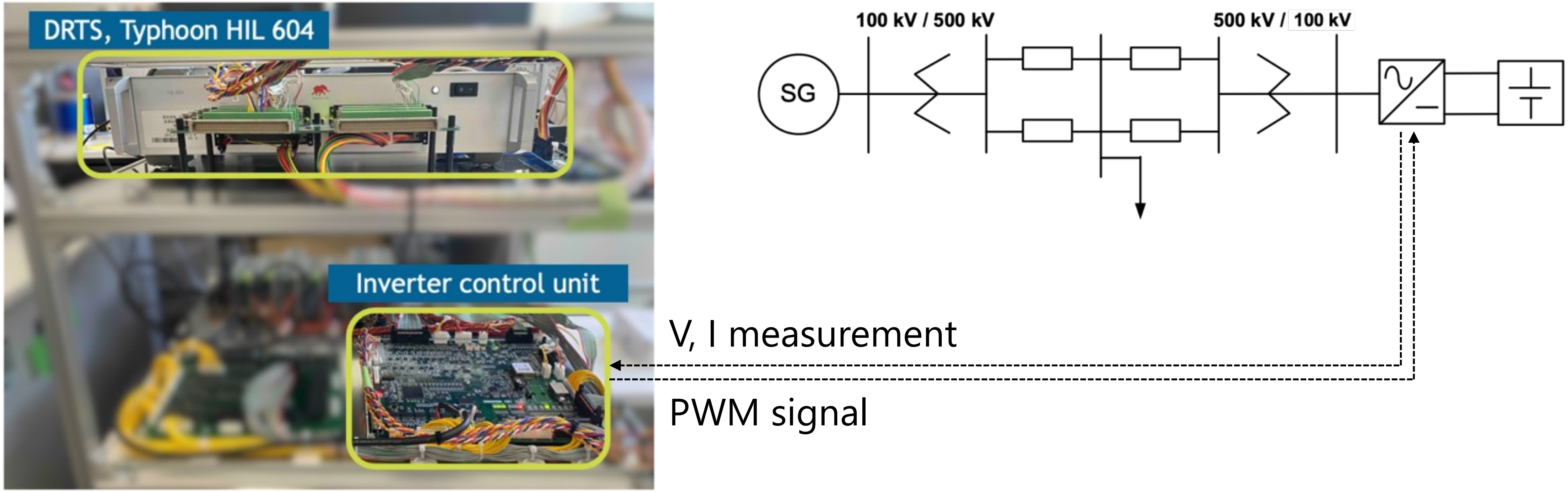
Source: J. Hashimoto, et al., "Developing a Synthetic Inertia Function for Smart Inverters and Studying its interaction with other functions with CHIL testing," Energy Reports 2023, 9 (supplement 1), 435–443.

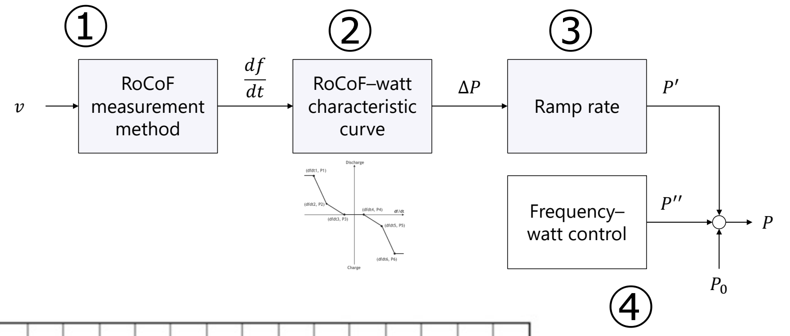
CHIL Setup for Parameter Sensitivity Analysis

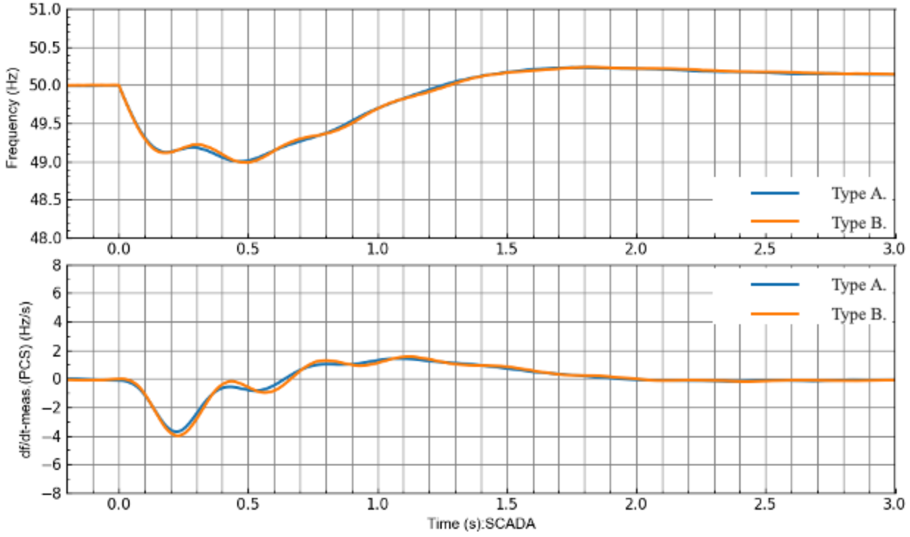


- Synchronous generator (SG): 300 kVA, 150 kW output
- Inverter-based resource (IBR): 300 kVA, 150 kW output
- Load: 300 kW => 320 kW

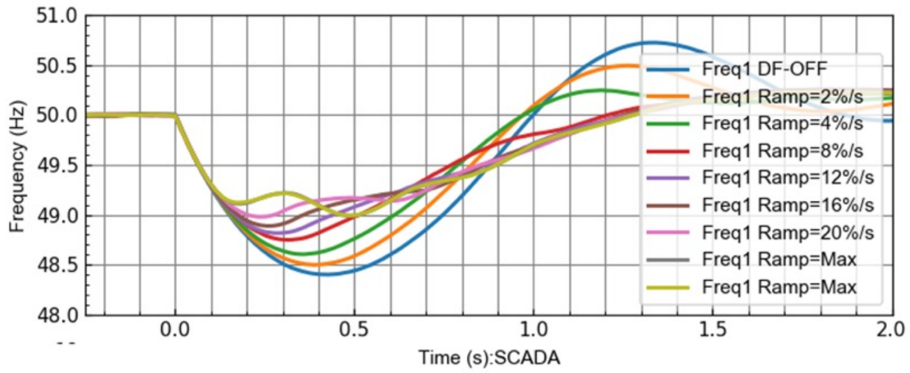
Source: J. Hashimoto, et al., "Developing a Synthetic Inertia Function for Smart Inverters and Studying its interaction with other functions with CHIL testing," Energy Reports 2023, 9 (supplement 1), 435–443.

Result of Parameter Sensitivity by CHIL Testing

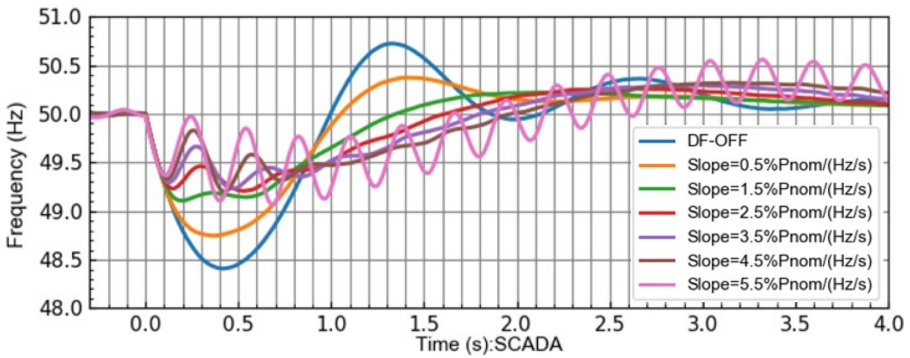




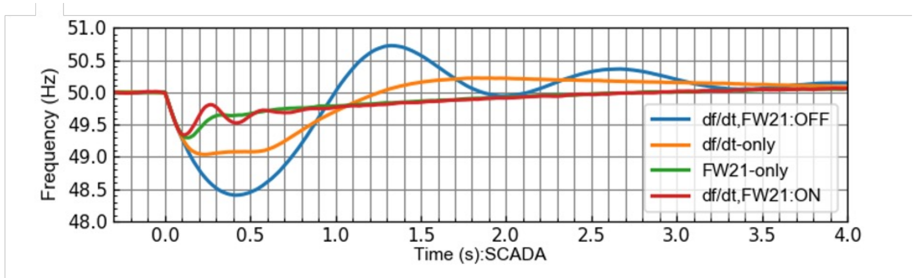
① RoFoC measurement method



③ Ramp rate



② RoCoF–watt curve



④ Frequency-watt control activation

Others: time window, dead band, etc.

Source: J. Hashimoto, et al., "Development of df/dt Function in Inverters for Synthetic Inertia," Energy Reports 2023, 9 (supplement 1), 363–371;
J. Hashimoto, et al., "Developing a Synthetic Inertia Function for Smart Inverters and Studying its interaction with other functions with CHIL testing," Energy Reports 2023, 9 (supplement 1), 435–443.

Pros and Cons of CHIL Testing

- Easy to implement, debug, and perform sensitivity analysis
  - Significant advantages for manufacturers

- Cannot evaluate performance including power unit
  - System operators may require the performance evaluation of the entire inverter
    - Simulation model submission
    - **PHIL testing**

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PHIL Testing for Performance Evaluation of Inverters from Different Manufacturers

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Tested Five Inverter Prototypes with Virtual Inertia Control

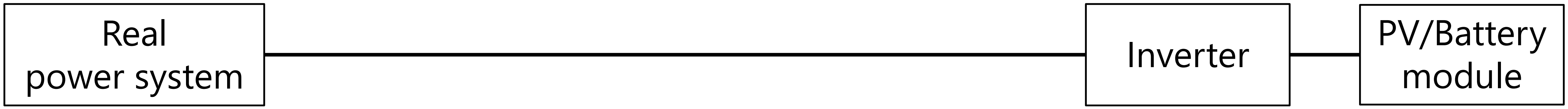
	Grid-following inverter		Grid-forming inverter		
	GFL 1	GFL 2	GFM 0	GFM 1	GFM 2
Control function	df/dt-P droop f-P droop	df/dt-P droop f-P droop	VSM Q-V droop	P-f droop Q-V droop	VSM Q-V droop
Rated capacity (kVA)	20	49.9	12	20	50
Rated AC voltage (V)	200	200	420	200	440



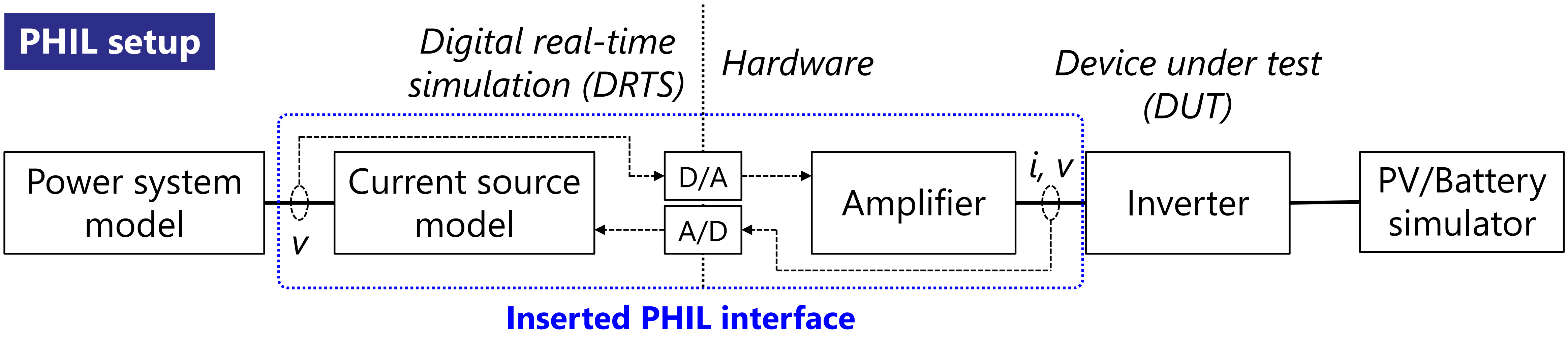

Major Challenges of PHIL Testing

- **PHIL interface is a key part that contributes to**
  - **Flexibility, stability, and accuracy of PHIL setup**
- Node limitation for real-time simulation
  - Node reduction modeling without loss of important information

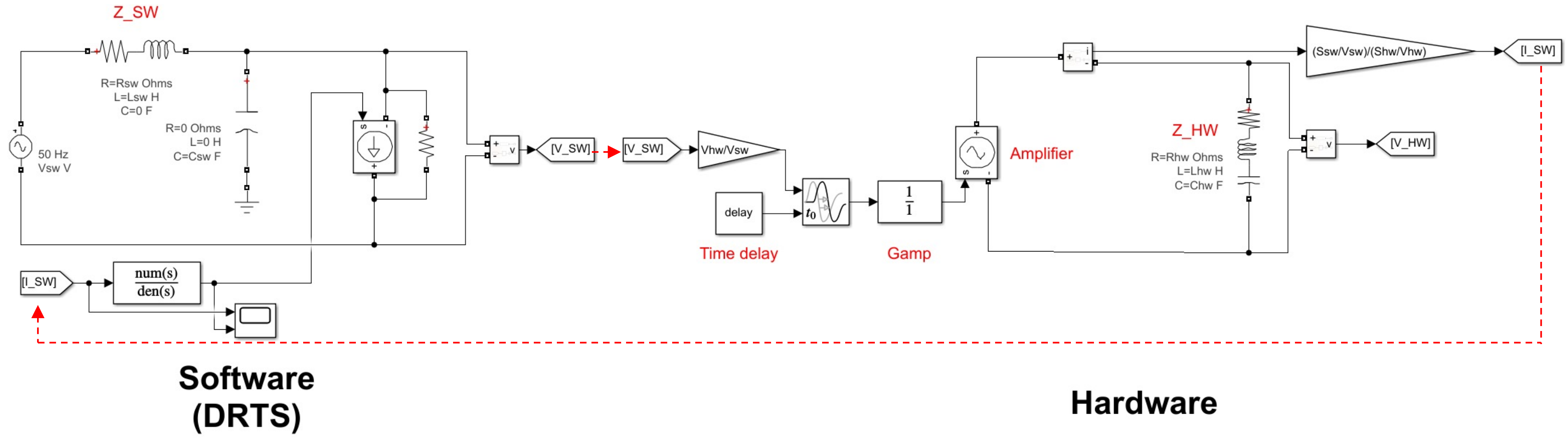
Real interconnection

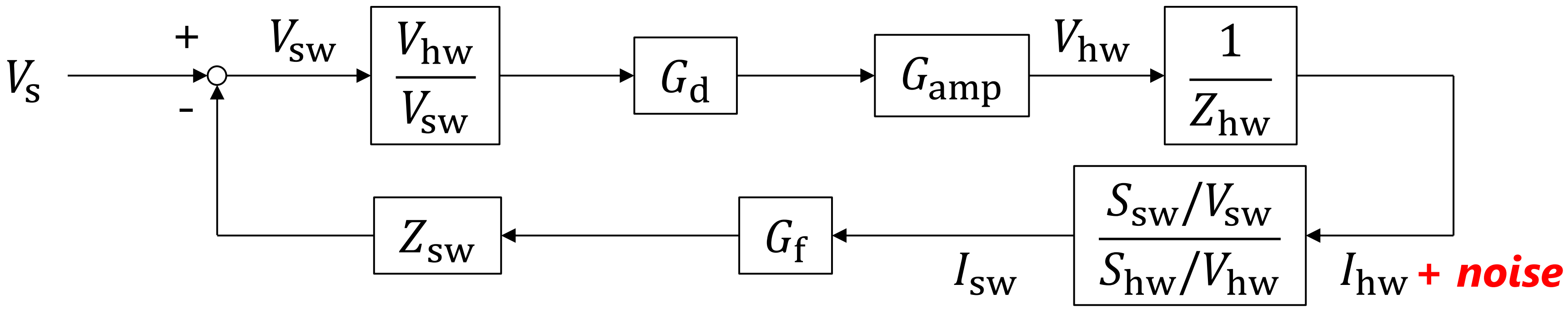


PHIL setup



Stability Assessment of PHIL Simulation





$$\frac{Z_{sw}}{Z_{hw}} \cdot \frac{S_{sw}/V_{sw}}{S_{hw}/V_{hw}} \cdot \frac{V_{hw}}{V_{sw}} > 1$$: Oscillating error continues to increase (intuitive understanding)

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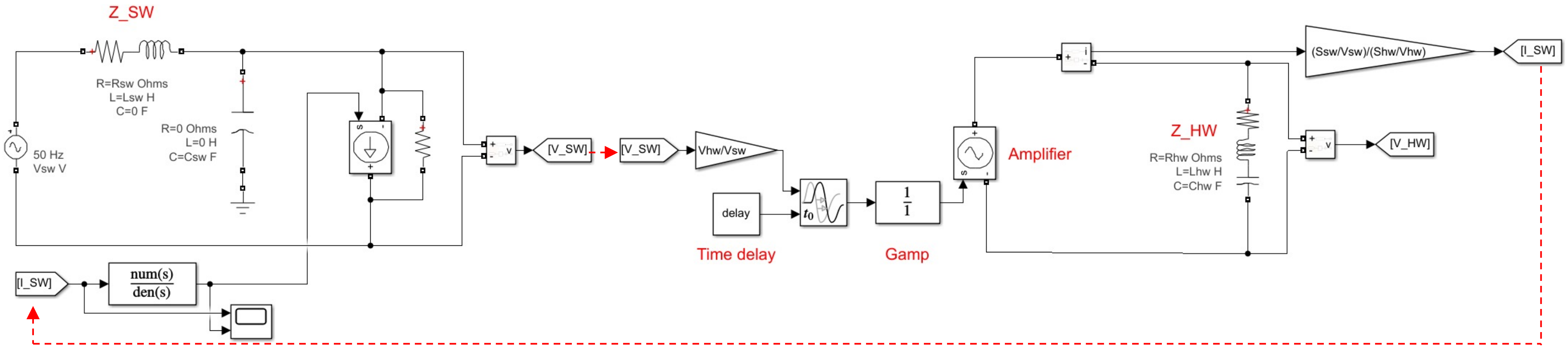
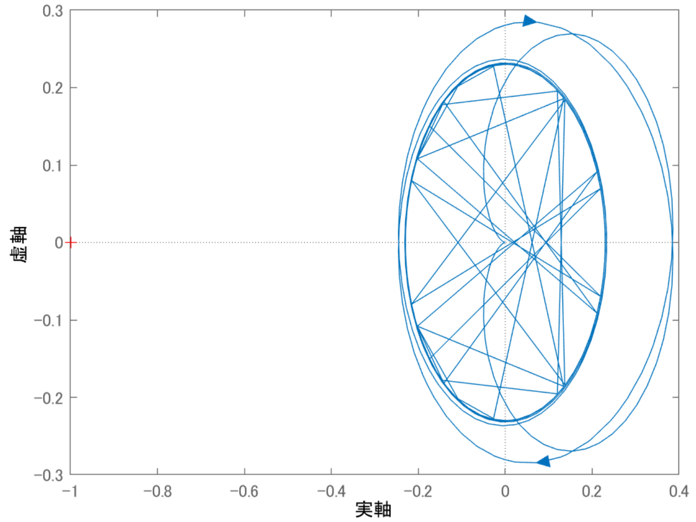
$S_{sw} = \mathbf{10\ MW}, \tau = 0\ \mu s$: **Stable**

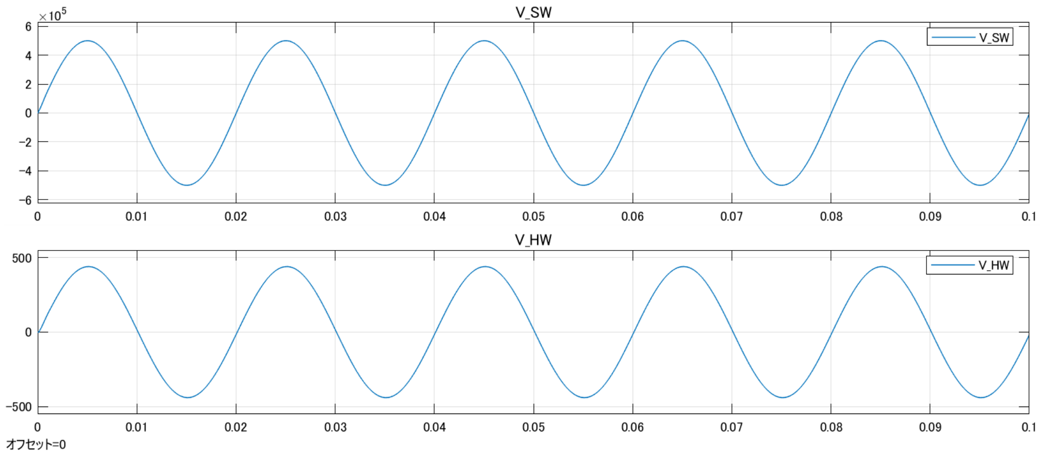


Software (DRTS)

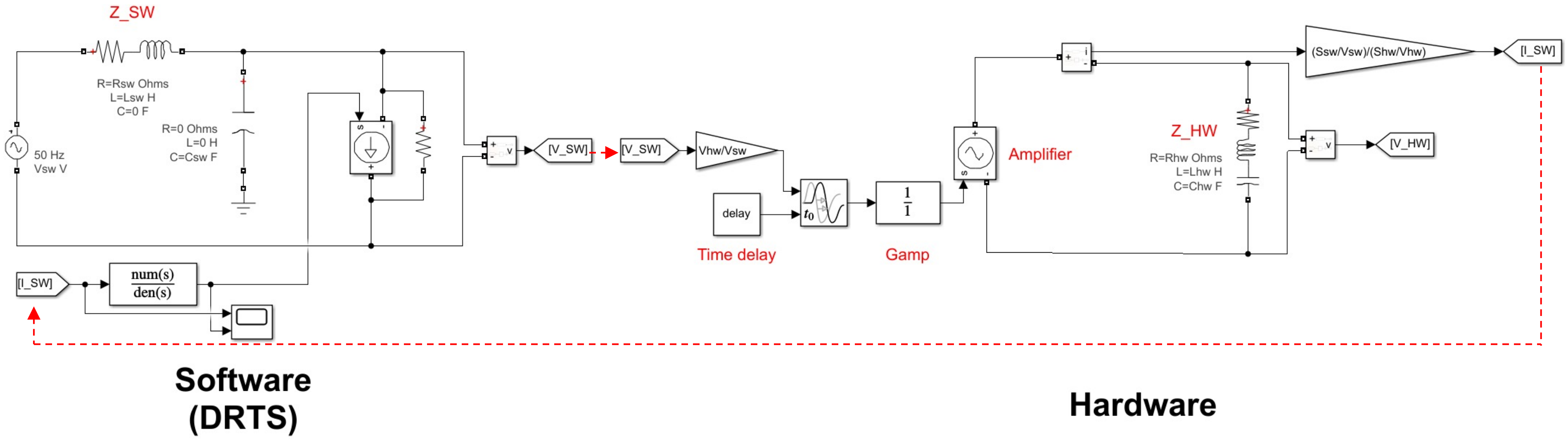
Hardware

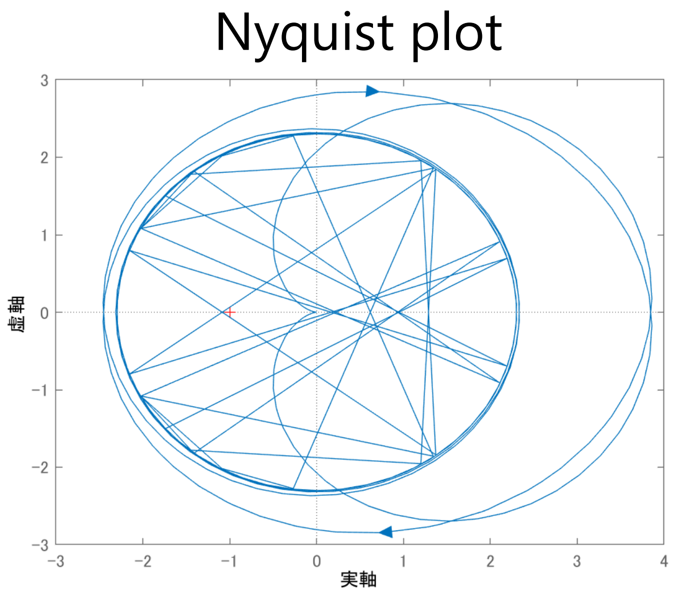
Nyquist plot

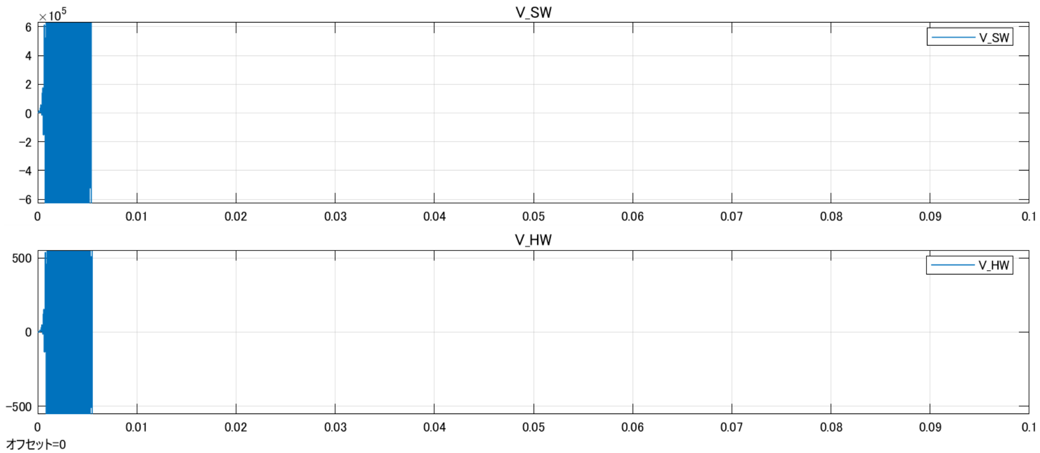




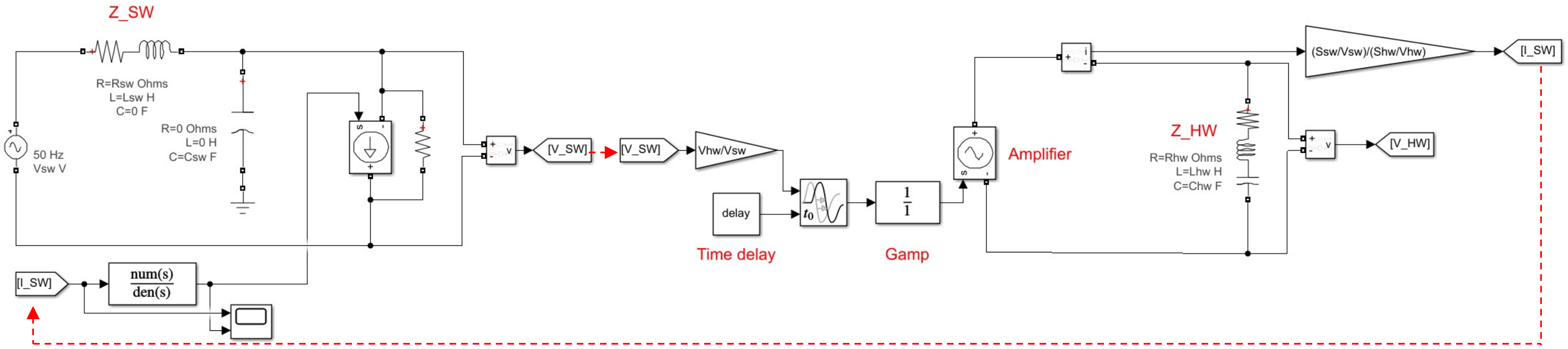
S_{sw} = 100 MW, τ = 0 μs : Unstable







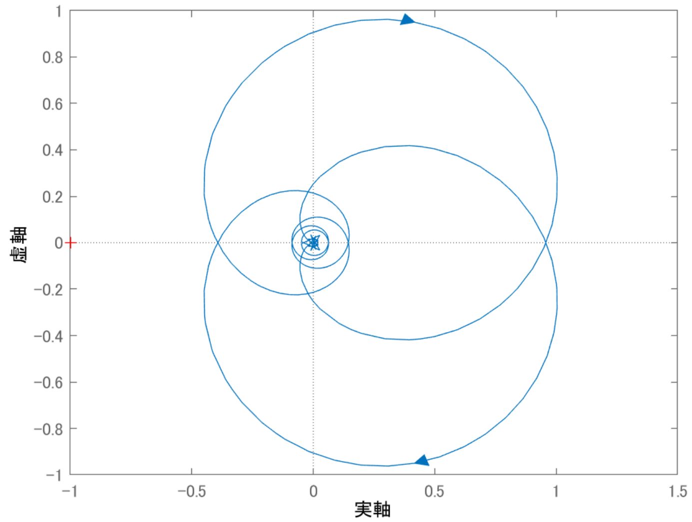
$S_{sw} = 100\ \mathrm{MW}, \tau = 500\ \mu s$: Stable

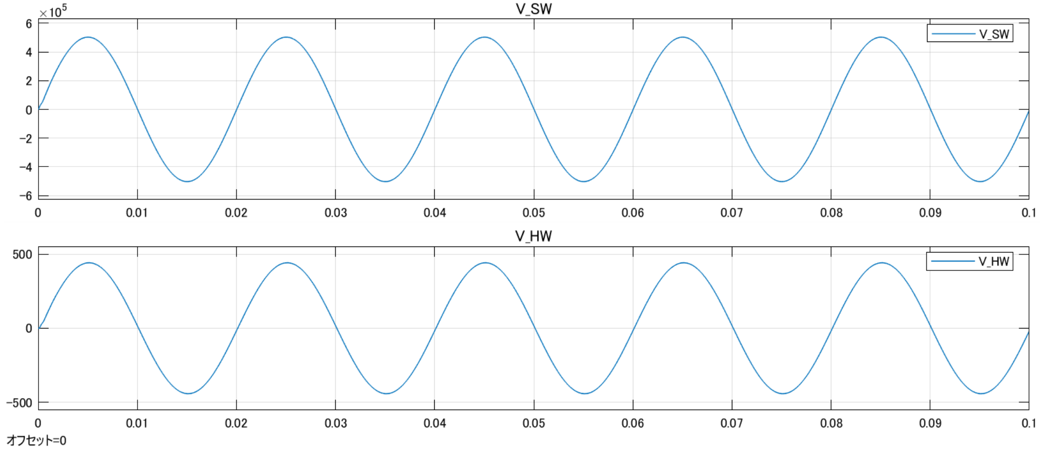


Software (DRTS)

Hardware

Nyquist plot





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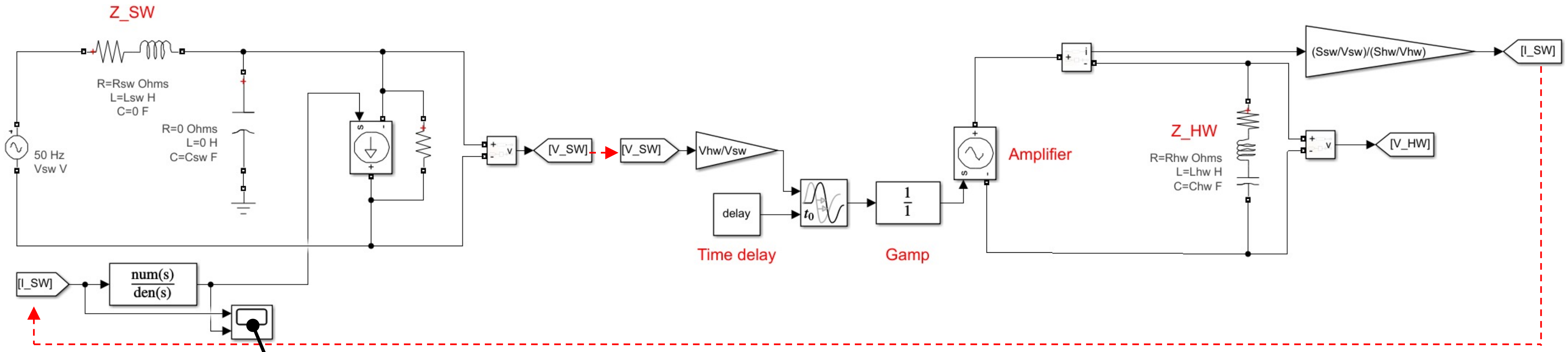
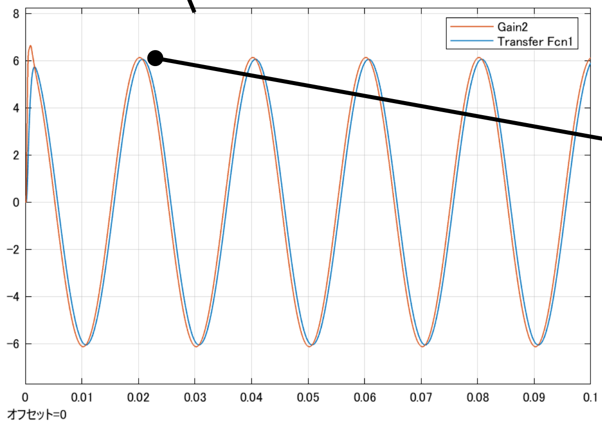
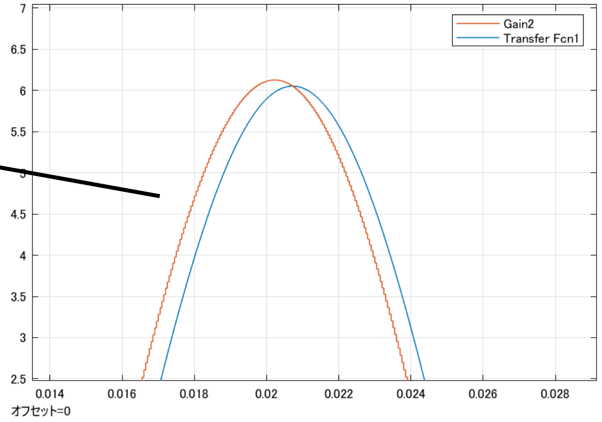
$S_{sw} = 100\ \mathrm{MW}, \tau = 500\ \mu s$: Stable, but Slightly Inaccurate



Software (DRTS)

Hardware





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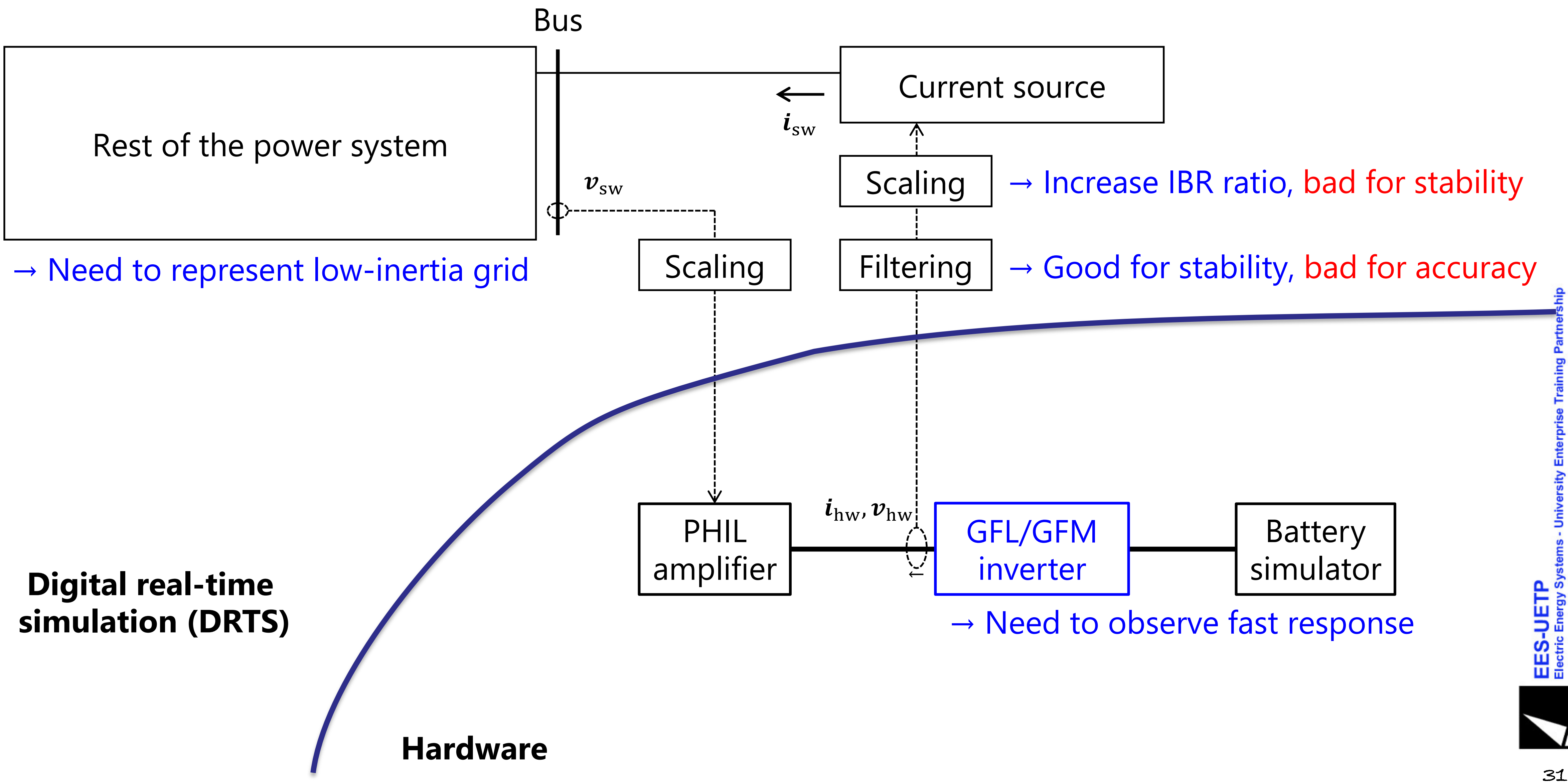
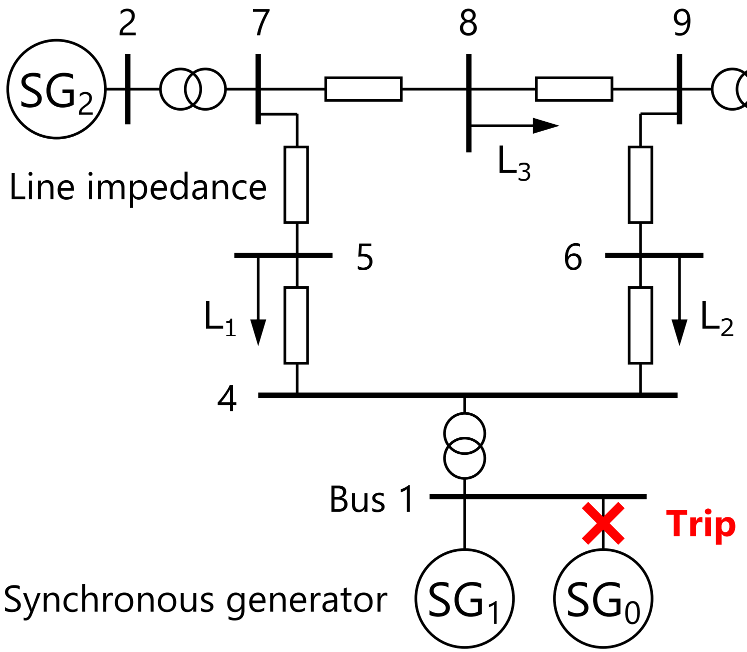
Building Stable and Accurate PHIL Environment of Low-Inertia Grid was Difficult



AIST FREA

PHIL Test Setup for GFL/GFM Inverters Using Modified IEEE 9-Bus System Model

Modified IEEE 9-bus system model (300 MW)



$\boldsymbol{v}_{\mathrm{sw}}$

$\boldsymbol{i}_{\mathrm{sw}}$

Dynamic PQ Source

$S_{\mathrm{sw}} = 60{,}120{,}180{,}240\ \mathrm{MVA}$
$V_{\mathrm{sw}} = 230\ \mathrm{kV}$

Scaling → Increase IBR ratio, bad for stability

Filtering → Good for stability, bad for accuracy

Scaling

Digital real-time simulation (DRTS)

Hardware

$S_{\mathrm{hw}} = 50\ \mathrm{kVA}$
$V_{\mathrm{hw}} = 440\ \mathrm{V}$

PHIL amplifier

$\boldsymbol{i}_{\mathrm{hw}}, \boldsymbol{v}_{\mathrm{hw}}$

GFL/GFM inverter

Battery simulator

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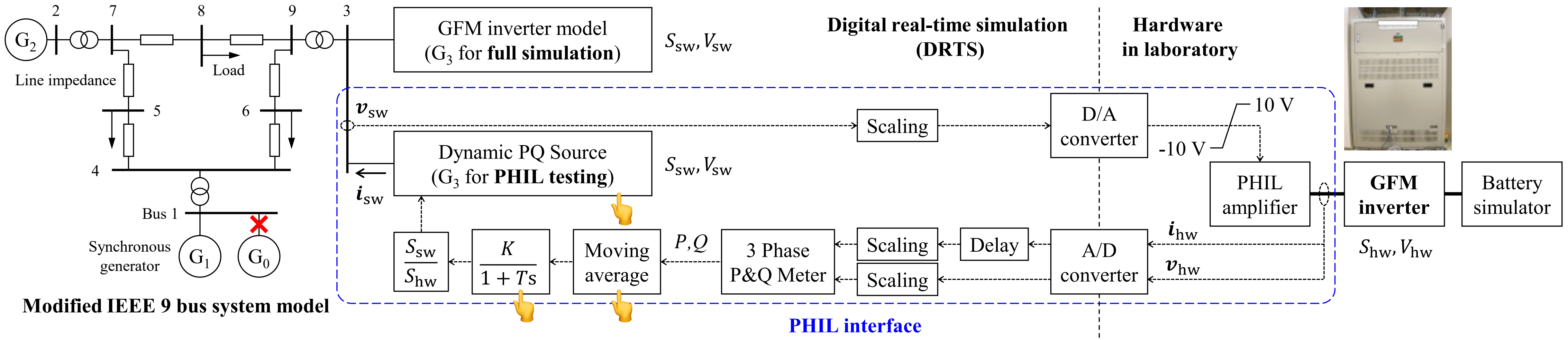
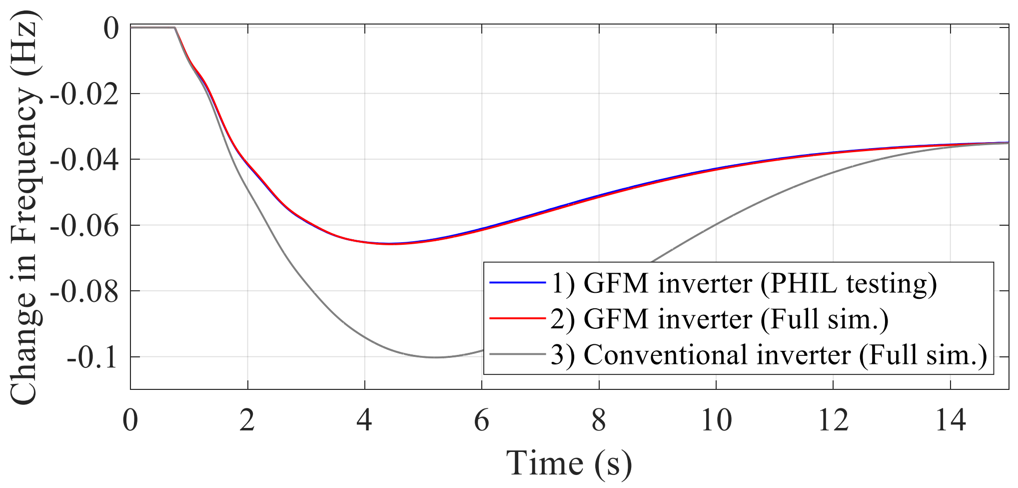
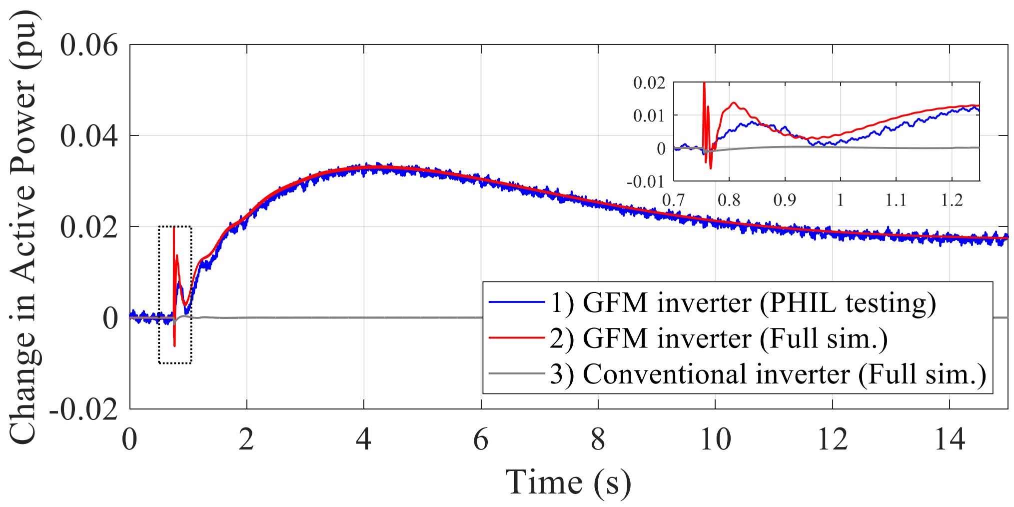
PHIL Testing Can be Conducted Stably in Most Cases with Adequate Accuracy





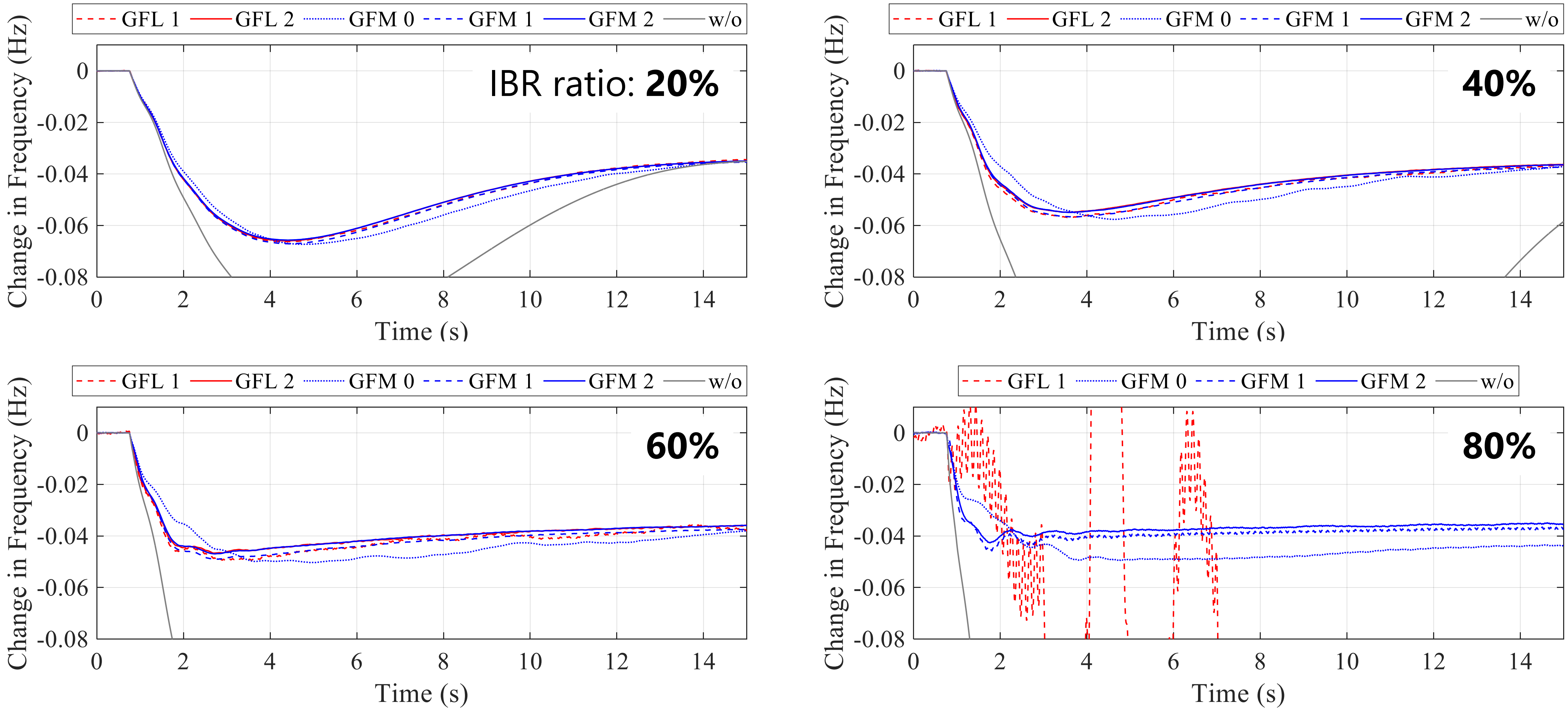
Frequency



Active power

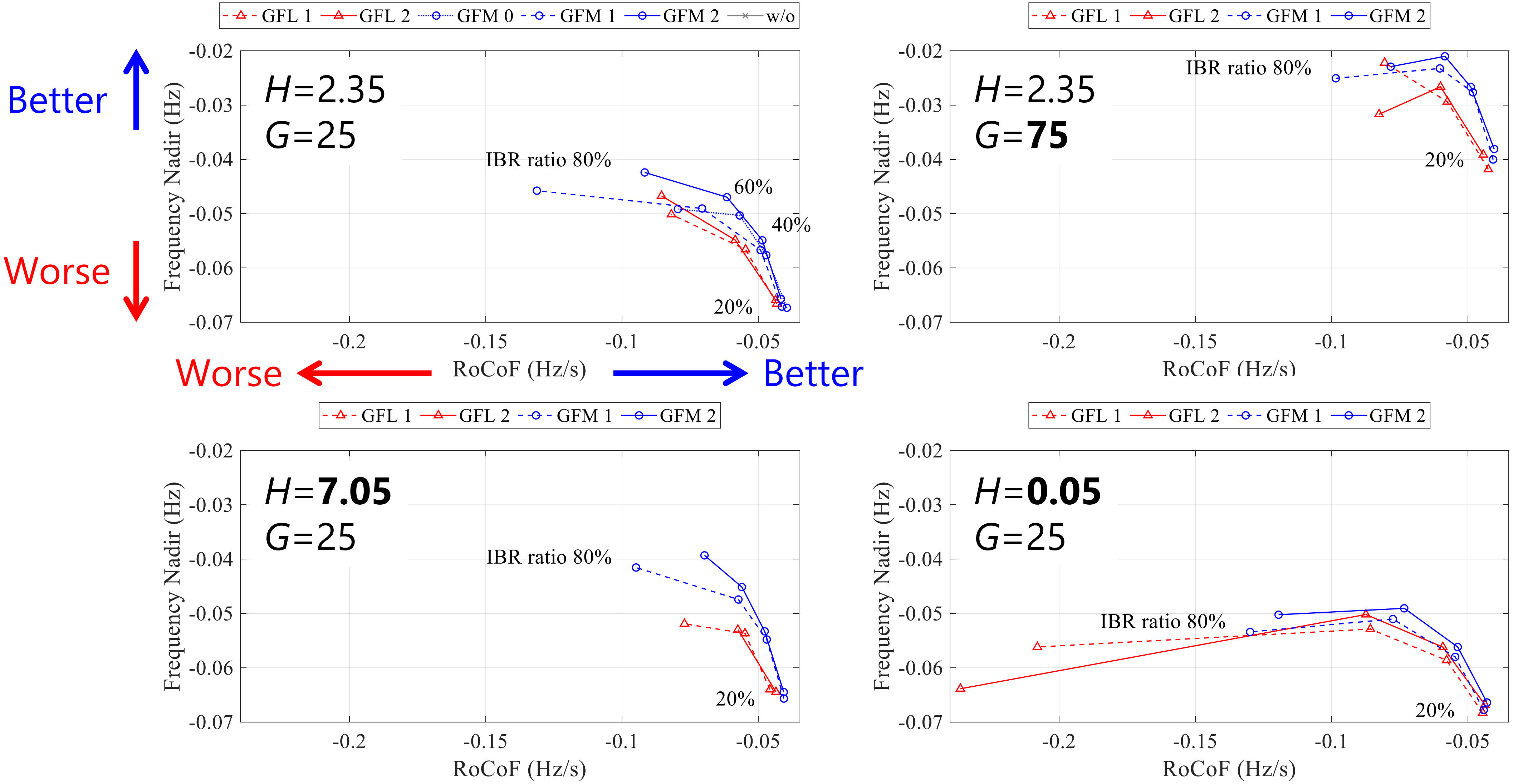
Source: H. Kikusato, et al., "Verification of Power Hardware-in-the-Loop Environment for Testing Grid-Forming Inverter," Energy Reports 2023, 9 (supplement 3), 303–311.

As IBR Ratio Increased, Frequency Change Increased for Conv. IBR, Decreased for GFL and GFM Inverters. GFM Inverters were Stable at 80%.



Source: H. Kikusato, et al., "Performance Evaluation of Grid-Following and Grid-Forming Inverters on Frequency Stability in Low-Inertia Power Systems by Power Hardware-in-the-Loop Testing," Energy Reports 2023, 9 (supplement 1), 381–392.

Inertia Constant "*H*" Affects RoCoF; Governor Gain "*G*" Affects Frequency Nadir (and RoCoF)



Source: H. Kikusato, et al., "Performance Evaluation of Grid-Following and Grid-Forming Inverters on Frequency Stability in Low-Inertia Power Systems by Power Hardware-in-the-Loop Testing," Energy Reports 2023, 9 (supplement 1), 381–392.

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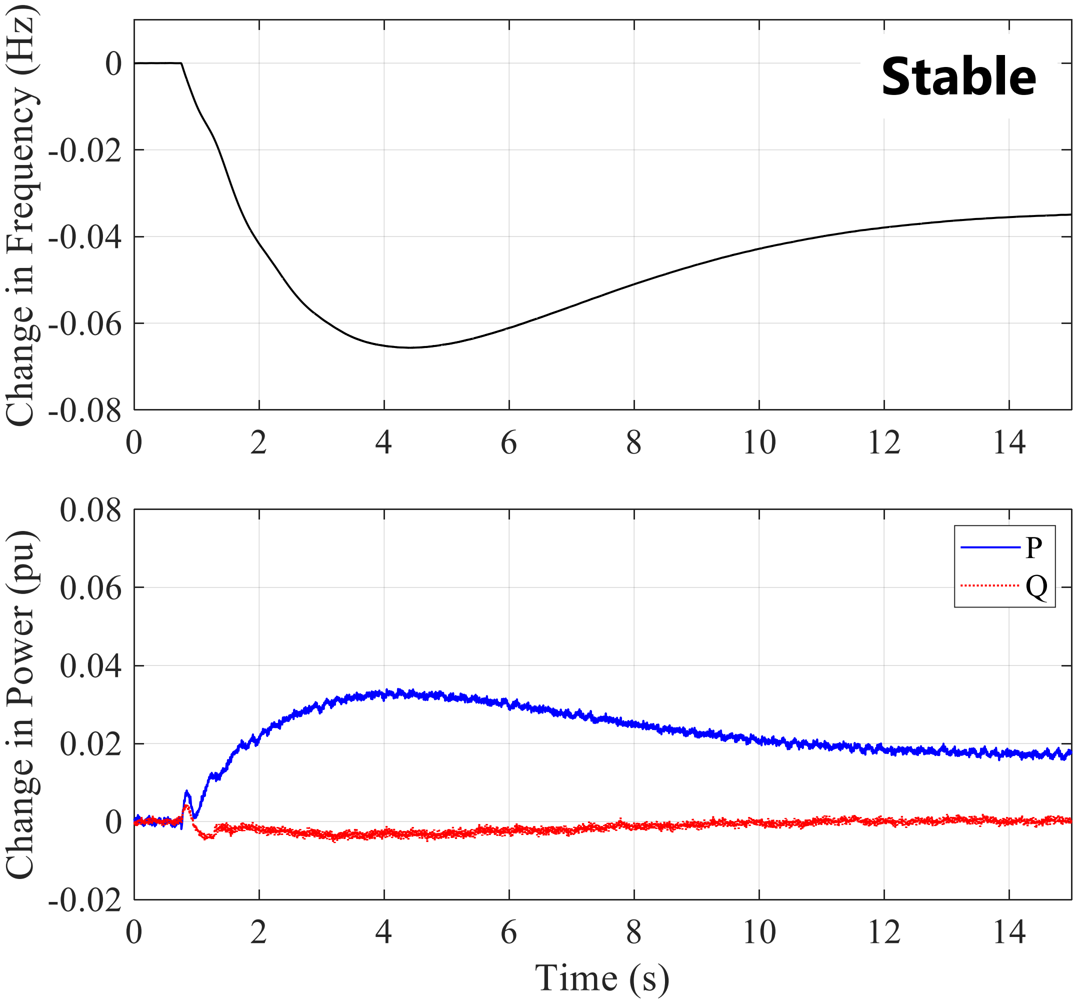
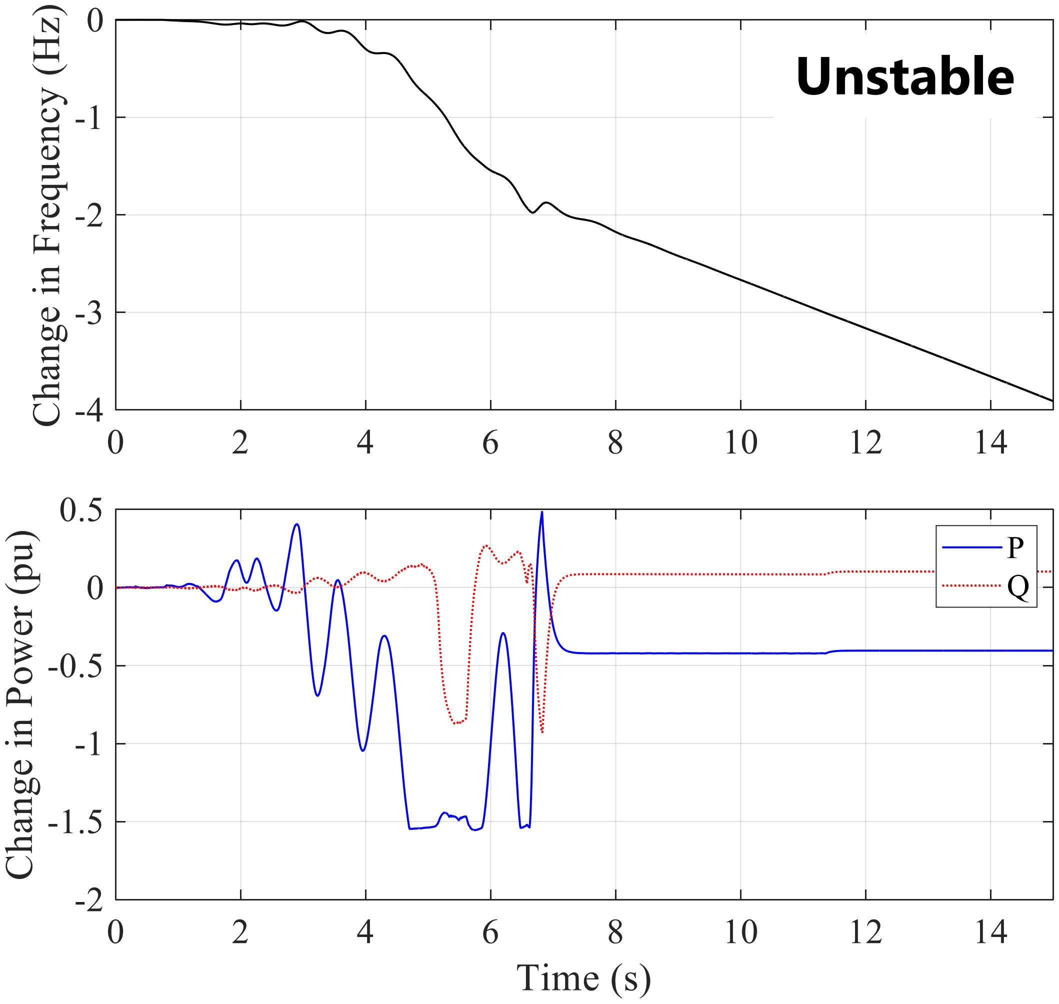
Interference Occurs between Islanding Detection and Frequency Stabilization Capability in GFM Inverter



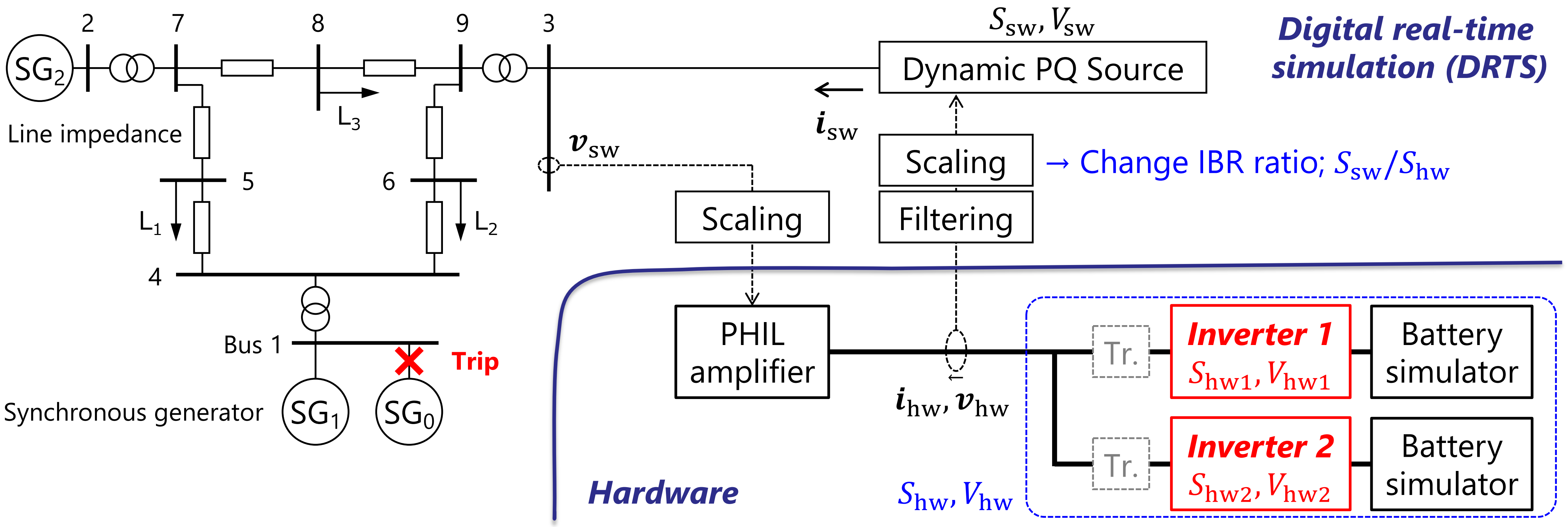
Disable islanding detection



Enable islanding detection

Source: H. Kikusato, et al., "Performance Evaluation of Grid-Following and Grid-Forming Inverters on Frequency Stability in Low-Inertia Power Systems by Power Hardware-in-the-Loop Testing," Energy Reports 2023, 9 (supplement 1), 381–392.

PHIL Testing for Multiple Inverter Combinations



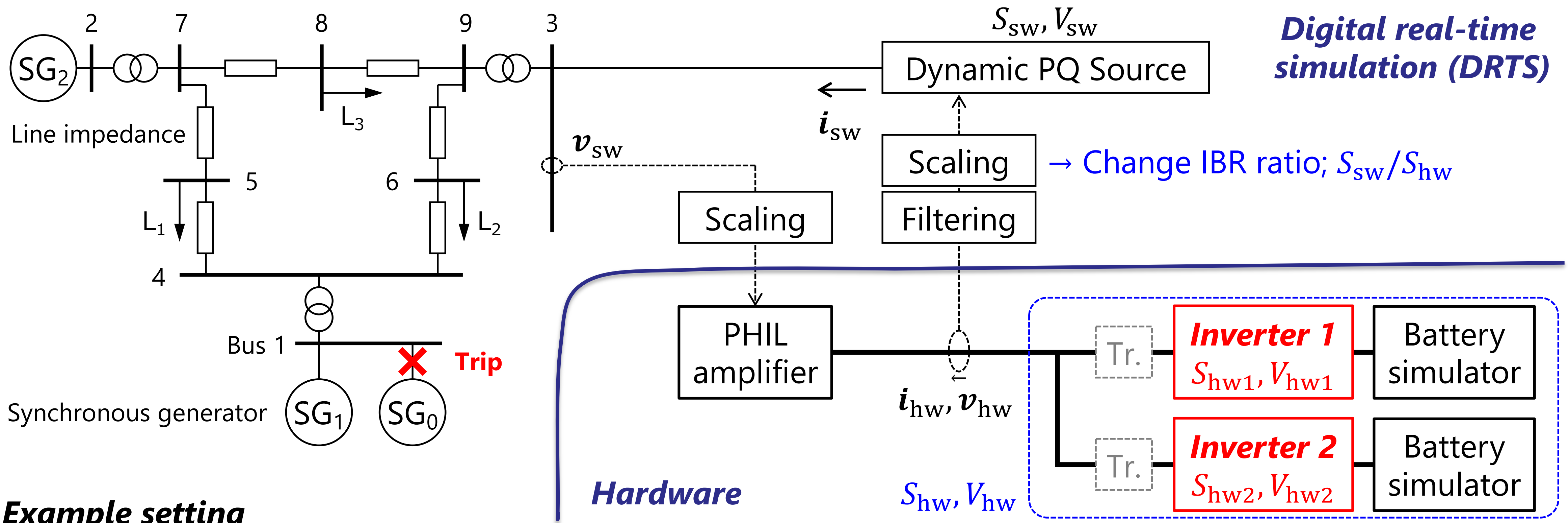
How do we test multiple inverters with different ratings?

▼

Equalize rated capacities, voltages, and control parameters

Source: H. Kikusato, et al., "Power Hardware-in-the-Loop Testing for Multiple Inverters with Virtual Inertia Controls," Energy Reports (accepted).

Configuration of PHIL Testing for Multiple Inverters

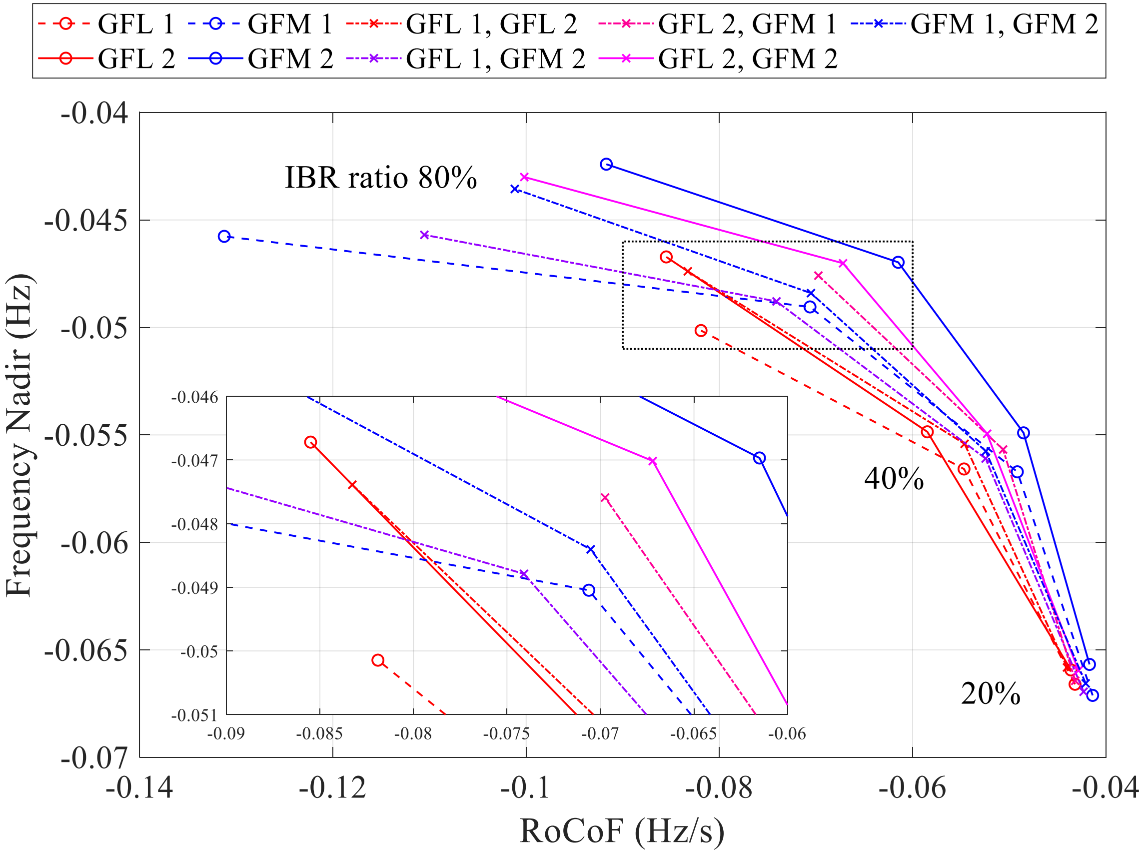


Example setting

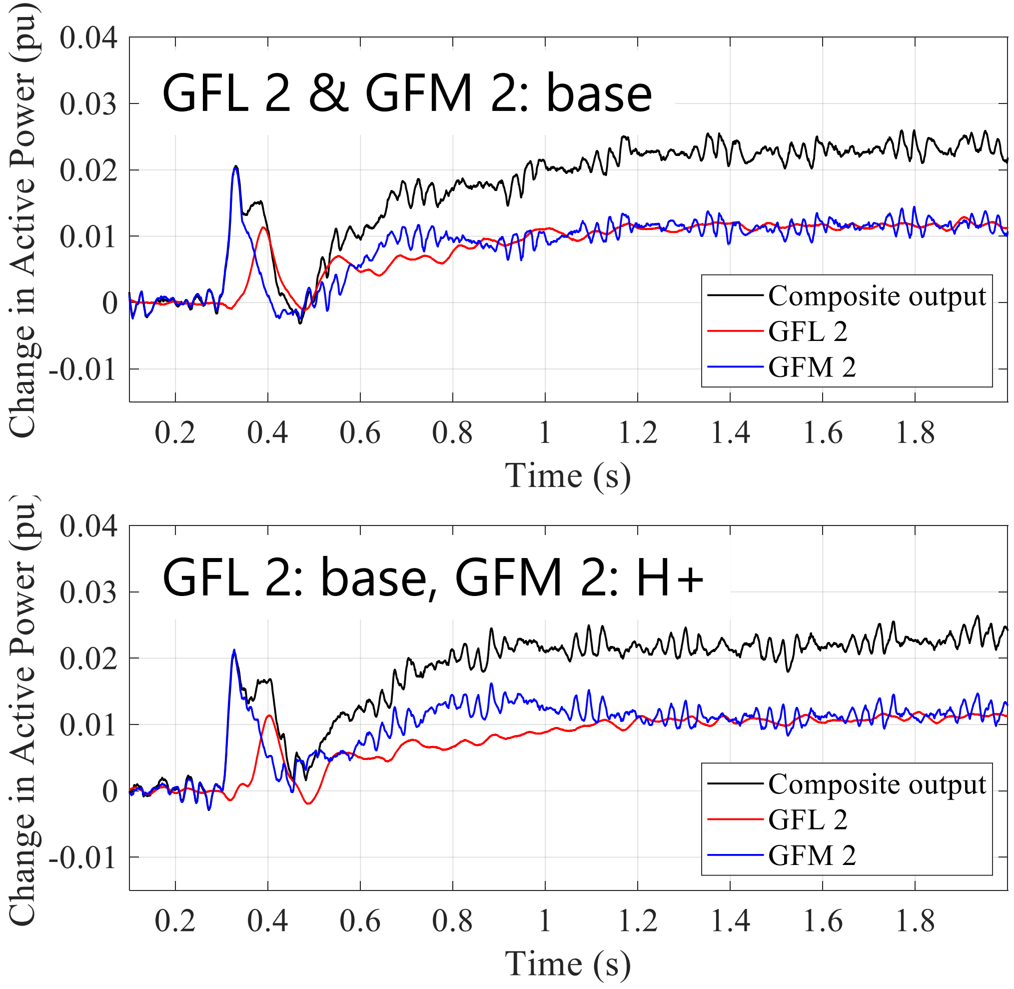
Inverter 1	$S_{hw1} = 20\text{ kVA} \Rightarrow S'_{hw1} = 20\text{ kVA}$	$V_{hw1} = 200\text{ V} \Rightarrow$ use Tr.	$H'_1 = \frac{S'_{hw1}}{S_{hw1}} \times H_1, G'_1 = \frac{S'_{hw1}}{S_{hw1}} \times G_1$
Inverter 2	$S_{hw2} = 50\text{ kVA} \Rightarrow S'_{hw2} = 20\text{ kVA}$	$V_{hw2} = 440\text{ V}$	$H'_2 = \frac{S'_{hw2}}{S_{hw2}} \times H_2, G'_2 = \frac{S'_{hw2}}{S_{hw2}} \times G_2$
Total setting	$S_{hw} = S'_{hw1} + S'_{hw2} = 40\text{ kVA}$	$V_{hw} = 440\text{ V}$	-

Source: H. Kikusato, et al., "Power Hardware-in-the-Loop Testing for Multiple Inverters with Virtual Inertia Controls," Energy Reports (accepted).

No inverter combination caused interference that significantly worsened the grid frequency stability. Combined inverters' performance was intermediate between the performance of each inverter alone.



RoCoF and frequency nadir



Active power

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Source: H. Kikusato, et al., "Power Hardware-in-the-Loop Testing for Multiple Inverters with Virtual Inertia Controls," Energy Reports (accepted).

Summary

- HIL testing is a powerful evaluation method for IBR dominant power systems
  - Can observe the interaction between IBRs and power systems
  - Can model various power systems and test inverter hardware (flexibility & fidelity)

- CHIL is simpler to implement, debug, and sensitivity analysis
  - Suitable for development phase by manufactures
  - Developed df/dt function for GFL inverter
  - Verified CHIL accuracy and performed many case studies

- PHIL is more realistic
  - Suitable for evaluation by utility
  - There are interface issues
  - Built accurate and stable PHIL test setup for GFL/GFM inverters in a low-inertia condition
  - Compared the performance of inverters from different manufacturers based on many case studies

Appendix

Conventional Japanese Conformance Testing

Tests with Changes in Voltage Magnitude, Frequency, and Phase Angle

- **GFL** Inverters: Almost **Conformance** in All Tests
- **GFM** Inverters: **Non-Conformance** in Most Tests, **Three Issues** are Identified

#	Test	GFL 1	GFL 2	GFM 0	GFM 1	GFM 2
1	Test for over/under-voltage trip	C*	C	N	N	N
2	Test for over/under-frequency trip	C*	C	N	N	N
3	Unintentional islanding test	C*	C*	-	N	C*
4	Test for voltage magnitude change within continuous operation region	C	C	N	C	C
5	Test for voltage phase angle change	C	C	C	N	N
6	Test for low/high-voltage ride-through	C*	C*	N	N	N
7	Test for low/high-frequency ride-through	C	C	N	N	C

C: Conformance; N: Non-conformance; -: Not conducted

* Conformance can be expected by minor changes to device configuration, control logic, etc.

Source: H. Kikusato, et al., "Performance Analysis of Grid-Forming Inverters in Existing Conformance Testing," Energy Reports 2022, 8 (supplement 15), 73–83.

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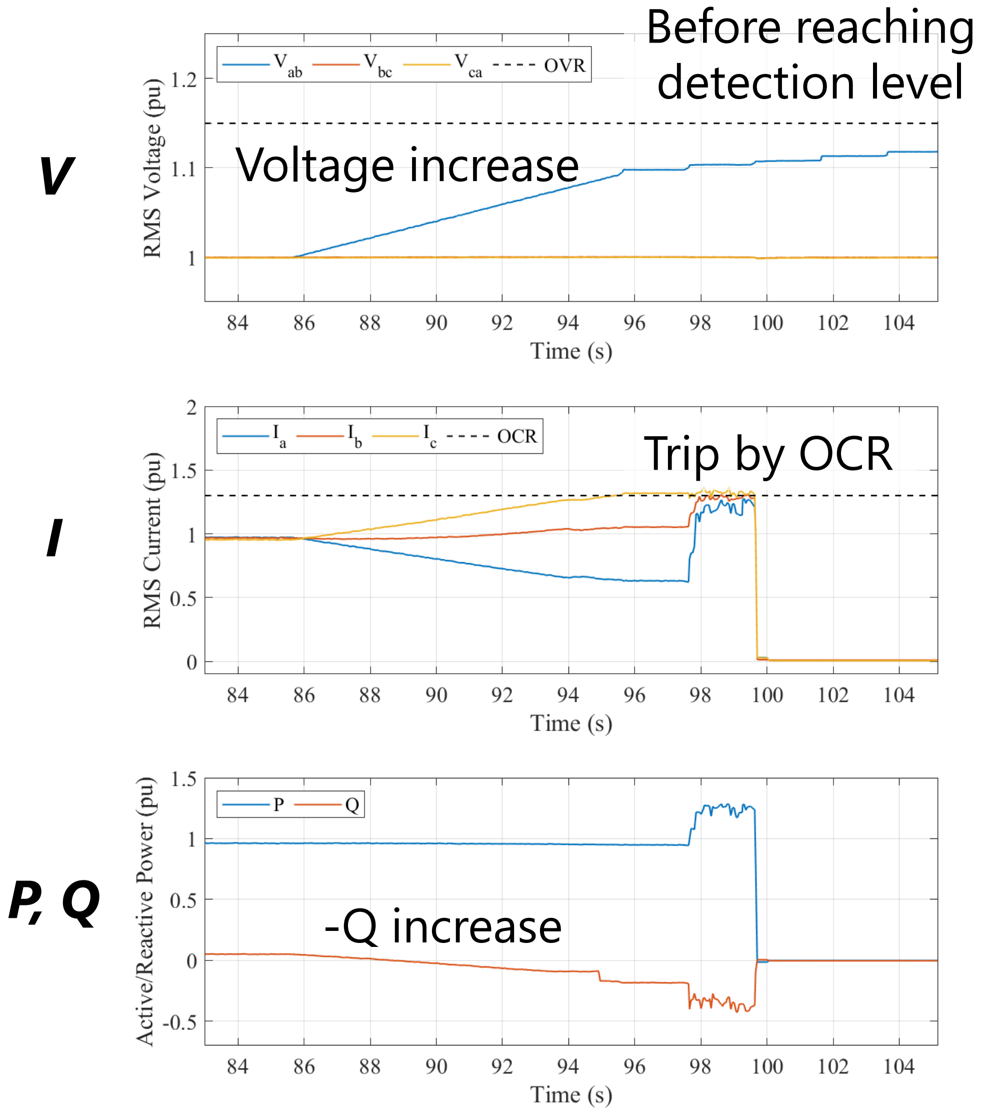
Issue 1: Unwanted Tripping by OCR due to Change in Grid Voltage



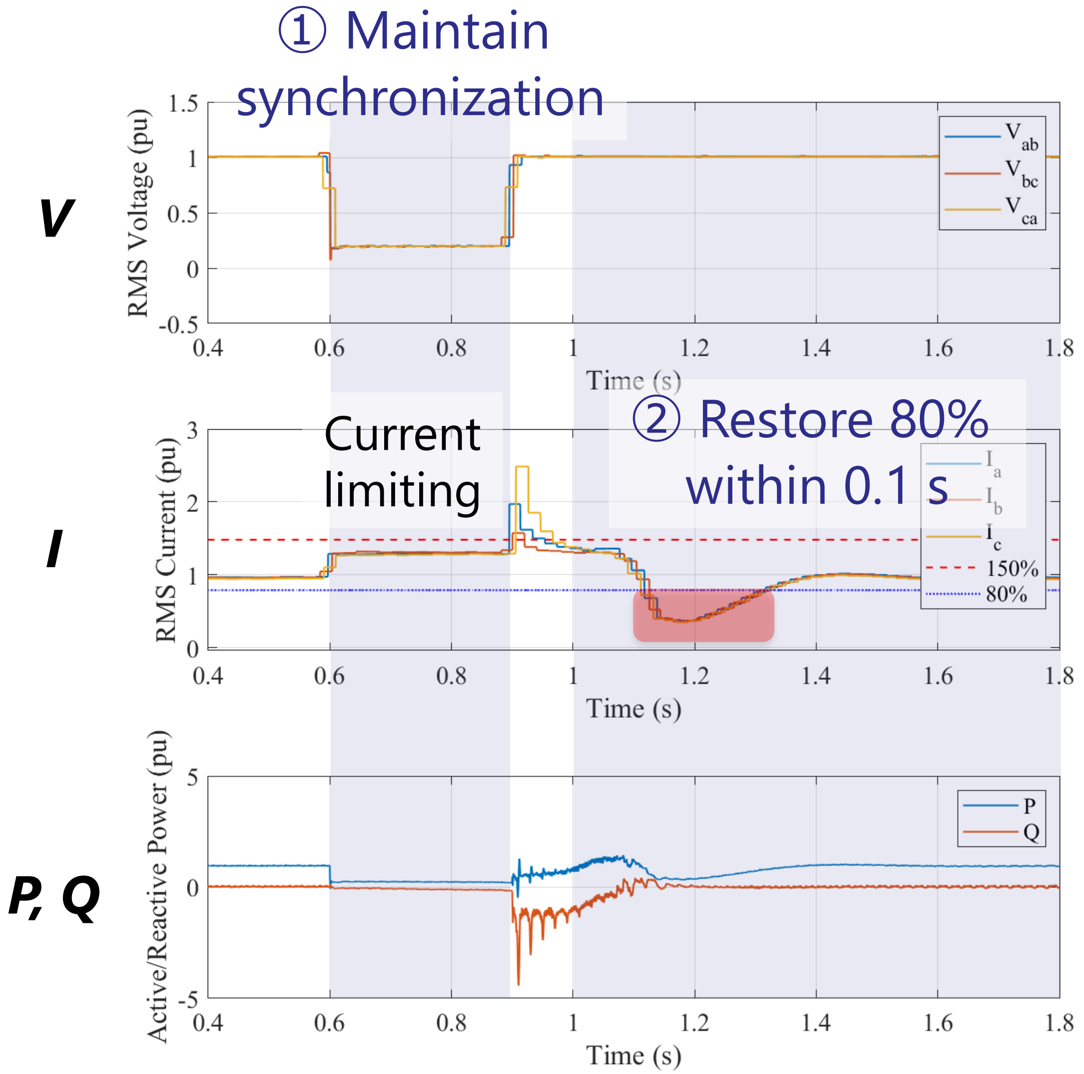
Test for over-voltage trip (GFM 0)

- Reason for non-conformance
  - Trip before initial state: #1, 2
  - Operation cannot continue: #4~7
- Reason for tripping due to OCR
  - GFM's voltage-source characteristic
  - No/short-term current limiting function
  - Initial P output setting was 1.0 pu
- Solution
  - Longer current limiting function
  - Decrease initial P output setting
  - Change control parameters

Source: H. Kikusato, et al., "Performance Analysis of Grid-Forming Inverters in Existing Conformance Testing," Energy Reports 2022, 8 (supplement 15), 73–83.

AIST FREA

Issue 2: Active Power Swing after Recovery from Voltage Sag



Low-voltage ride-through test (GFM 0)

- Reason for non-conformance
  - ② is not satisfied
- Reason for active power swing
  - GFM's voltage-source characteristic
- Solution
  - Change control logic/parameters
  - **Change conformance criteria**
- Cf. Conformance criteria of active power swing after voltage recovery
  - Acceptable: IEEE 1547, IEEE 2800, National Grid
  - Not noted: EN50549

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Source: H. Kikusato, et al., "Performance Analysis of Grid-Forming Inverters in Existing Conformance Testing," Energy Reports 2022, 8 (supplement 15), 73–83.

AIST FREA

Issue 3: Coexistence of Grid Stabilization Capability and Islanding Detection

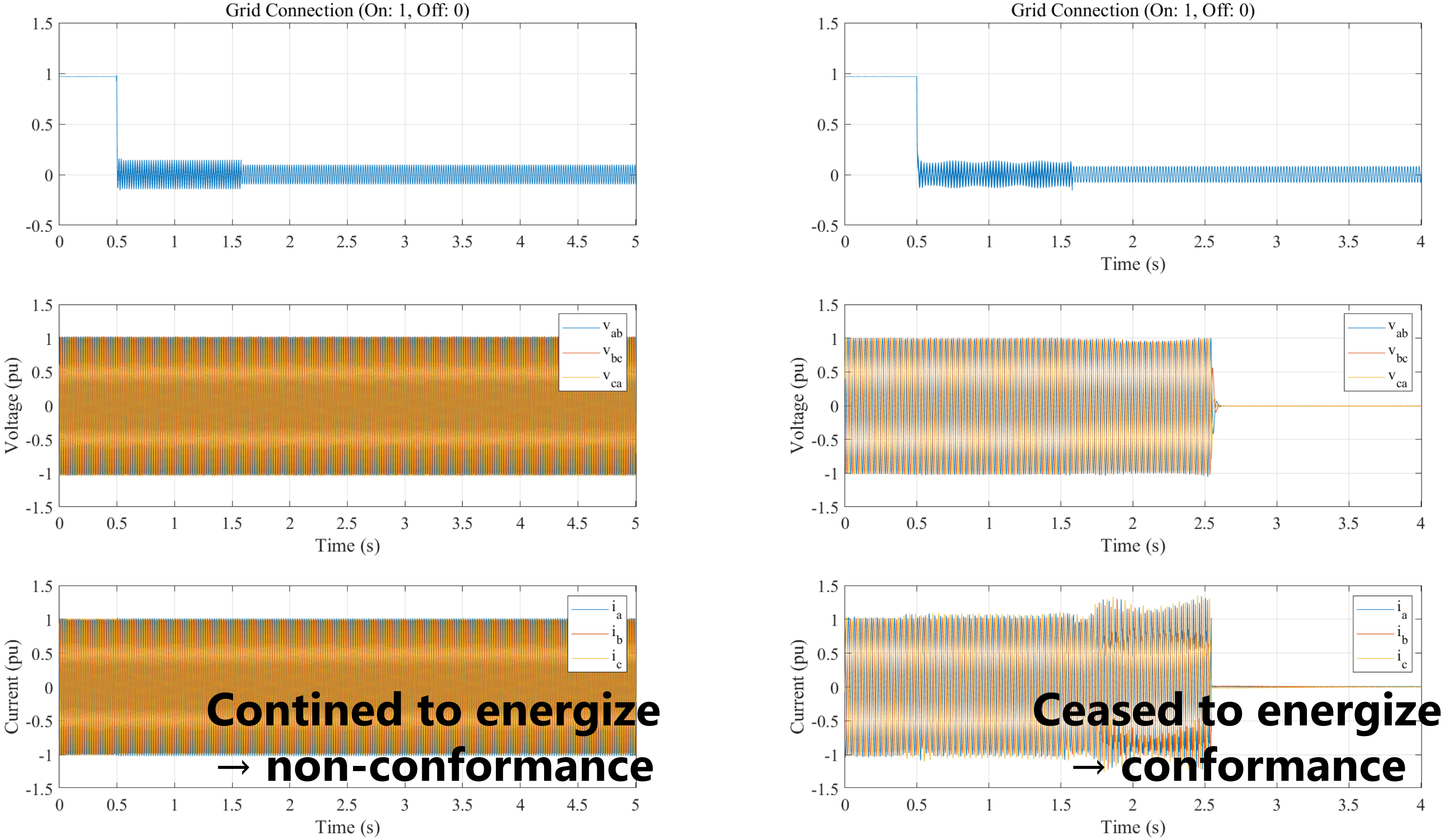
- **GFM 0**: not implemented, **GFM 1**: non-conformance but frequency was stabilized, **GFM 2**: conformance but frequency wasn’t stabilized

Unintentional islanding test result

Grid connection state

v

i



Contined to energize → non-conformance

Ceased to energize → conformance

GFM 1 **GFM 2**

Source: H. Kikusato, et al., "Performance Analysis of Grid-Forming Inverters in Existing Conformance Testing," Energy Reports 2022, 8 (supplement 15), 73–83.

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AIST FREA

Issue 3: Coexistence of Grid Stabilization Capability and Islanding Detection

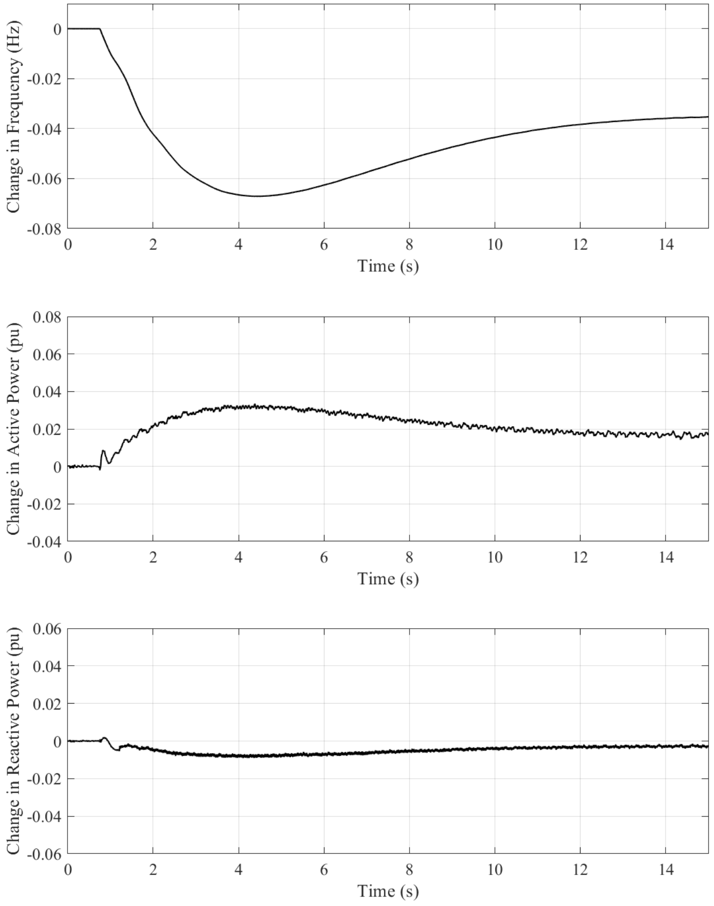
- **GFM 0**: not implemented, **GFM 1**: non-conformance but frequency was stabilized, **GFM 2**: conformance but frequency wasn't stabilized

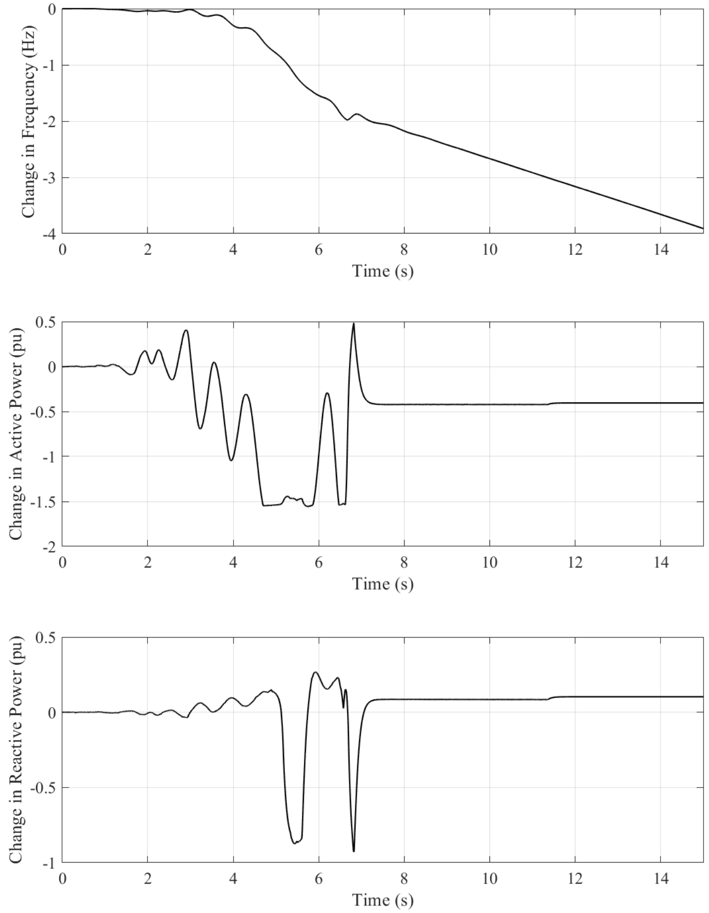
PHIL test results activating IDM (Kikusato et at., 2022)

f

P

Q





GFM 1
Frequency was stable

GFM 2
Frequency was unstable

Source: H. Kikusato, et al., "Performance Analysis of Grid-Forming Inverters in Existing Conformance Testing," Energy Reports 2022, 8 (supplement 15), 73–83.

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Related Works

- H. Kikusato et al., "Performance Evaluation of Grid-Following and Grid-Forming Inverters on Frequency Stability in Low-Inertia Power Systems by Power Hardware-in-the-Loop Testing," Energy Reports 2023, 9 (supplement 1), 381–392.
- H. Kikusato et al., "Performance Analysis of Grid-Forming Inverters in Existing Conformance Testing," Energy Reports 2022, 8 (supplement 15), 73–83.
- H. Kikusato et al., "Verification of Power Hardware-in-the-Loop Environment for Testing Grid-Forming Inverter," Energy Reports 2023, 9 (supplement 3), 303–311.
- H. Kikusato et al., "Power Hardware-in-the-Loop Testing for Multiple Inverters with Virtual Inertia Controls," Energy Report (accepted).
- D. Orihara et al., "Contribution of Voltage Support Function to Virtual Inertia Control Performance of Inverter-Based Resource in Frequency Stability," Energies 2021, 14, 4220.
- D. Orihara et al., "Internal Induced Voltage Modification for Current Limitation in Virtual Synchronous Machine," Energies 2022, 15, 901.
- J. Hashimoto et al., "Development of df/dt Function in Inverters for Synthetic Inertia," Energy Reports 2023, 9 (supplement 1), 363–371.
- J. Hashimoto et al., "Developing a Synthetic Inertia Function for Smart Inverters and Studying its Interaction with Other Functions with CHIL Testing," Energy Reports 2023, 9 (supplement 1), 435–443.
- T. Takamatsu et al., "Simulation Analysis of Issues with Grid Disturbance for a Photovoltaic Powered Virtual Synchronous Machine," Energies 2022, 15, 5921.
- H. Hamada et al., "Challenges for a Reduced Inertia Power System Due to the Large-Scale," Global Energy Interconnection 2022, 5(3), 266–273.

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